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(12) **United States Patent**  
**Grunwald et al.**

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(54) **ENDOVASCULAR DEVICES AND METHODS OF USE**

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**Related U.S. Application Data**

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(51) **Int. Cl.**  
**A61B 5/06** (2006.01)  
**A61B 5/026** (2006.01)

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(52) **U.S. Cl.**  
CPC ..... **A61B 5/065** (2013.01); **A61B 5/0205** (2013.01); **A61B 5/026** (2013.01); **A61B 5/042** (2013.01);

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(58) **Field of Classification Search**  
CPC ..... A61B 5/021; A61B 5/026; A61B 5/065  
USPC ..... 600/407, 437, 438, 450, 454, 459, 462, 600/465–467, 470

See application file for complete search history.

(56) **References Cited**

**U.S. PATENT DOCUMENTS**

3,565,062 A 2/1971 Kuris  
4,143,650 A 3/1979 Hatke

(Continued)

**FOREIGN PATENT DOCUMENTS**

CN 2031655 U 2/1989  
CN 1628602 A 6/2005

(Continued)

**OTHER PUBLICATIONS**

Bossert et al.; Swan-Ganz catheter-induced severe complications in cardiac surgery: right ventricular perforation, knotting, and rupture of a pulmonary artery; J. Car. Surg.; vol. 21; No. 3; pp. 292-295; May/Jun. 2006.

(Continued)

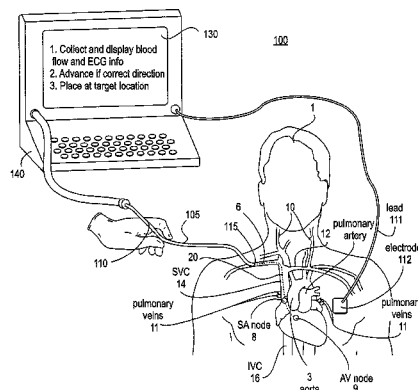
*Primary Examiner* — Rochelle Turchen

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(57) **ABSTRACT**

A method for evaluating flow characteristics in a vessel of a patient includes the steps of positioning a catheter having a balloon at a measuring location within the vessel; transmitting an ultrasound signal into the vessel while the balloon catheter is within the measuring location; evaluating a reflection of the ultrasound signal to determine a flow parameter within the vessel while the catheter is in the measuring position; expanding the balloon within the vessel at the measuring location; and stopping the expanding step when the result of the evaluating step is that the flow through the vessel is substantially stopped. In some embodiments, the method may further comprise the step of detecting an endovascular electrogram signal. The method may be designed for evaluating flow characteristics in a vessel of a patient while enabling the prevention of a balloon from over-expanding and/or over-distending a vessel of a patient.

**37 Claims, 26 Drawing Sheets**



**Related U.S. Application Data**

9,204,819, said application No. 12/147,401 is a continuation-in-part of application No. 11/431,118, filed on May 8, 2006, now Pat. No. 9,198,600, said application No. 12/147,401 is a continuation-in-part of application No. 11/431,093, filed on May 8, 2006, now abandoned, said application No. 12/147,401 is a continuation-in-part of application No. 11/430,511, filed on May 8, 2006, now Pat. No. 8,409,103.

- (60) Provisional application No. 60/937,280, filed on Jun. 26, 2007, provisional application No. 60/957,316, filed on Aug. 22, 2007, provisional application No. 61/023,183, filed on Jan. 24, 2008, provisional application No. 60/678,209, filed on May 6, 2005, provisional application No. 60/682,002, filed on May 18, 2005, provisional application No. 61/023,176, filed on Jan. 24, 2008, provisional application No. 61/023,179, filed on Jan. 24, 2008.

**(51) Int. Cl.**

*A61B 5/042* (2006.01)  
*A61B 8/06* (2006.01)  
*A61B 8/12* (2006.01)  
*A61B 8/00* (2006.01)  
*A61B 19/00* (2006.01)  
*G09B 23/28* (2006.01)  
*A61B 5/0205* (2006.01)  
*A61B 7/04* (2006.01)  
*A61B 5/0215* (2006.01)  
*A61B 5/029* (2006.01)  
*A61B 5/0452* (2006.01)  
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*A61B 5/1459* (2006.01)  
*A61B 8/08* (2006.01)  
*A61B 17/00* (2006.01)  
*A61B 17/22* (2006.01)

**(52) U.S. Cl.**

CPC . *A61B 5/06* (2013.01); *A61B 5/061* (2013.01);  
*A61B 7/04* (2013.01); *A61B 8/06* (2013.01);  
*A61B 8/0841* (2013.01); *A61B 8/12* (2013.01);  
*A61B 8/42* (2013.01); *A61B 8/445* (2013.01);  
*A61B 19/5244* (2013.01); *G09B 23/288*  
(2013.01); *A61B 5/029* (2013.01); *A61B 5/0215*  
(2013.01); *A61B 5/0452* (2013.01); *A61B*  
*5/0472* (2013.01); *A61B 5/0476* (2013.01);  
*A61B 5/1459* (2013.01); *A61B 8/08* (2013.01);  
*A61B 8/463* (2013.01); *A61B 8/465* (2013.01);  
*A61B 8/565* (2013.01); *A61B 19/56* (2013.01);  
*A61B 2017/00044* (2013.01); *A61B 2017/00106*  
(2013.01); *A61B 2017/00115* (2013.01); *A61B*  
*2017/22067* (2013.01); *A61B 2019/462*  
(2013.01); *A61B 2019/464* (2013.01); *A61B*  
*2019/5251* (2013.01); *A61B 2019/5255*  
(2013.01); *A61B 2019/5276* (2013.01); *A61B*  
*2019/562* (2013.01)

**(56) References Cited****U.S. PATENT DOCUMENTS**

4,319,580 A 3/1982 Colley et al.  
4,324,258 A 4/1982 Huebscher et al.  
4,354,502 A 10/1982 Colley et al.  
4,362,166 A 12/1982 Furler et al.  
4,503,861 A 3/1985 Entrekin

4,549,879 A 10/1985 Groshong et al.  
4,583,552 A \* 4/1986 Iinuma ..... 600/455  
4,644,960 A 2/1987 Johans  
4,660,565 A \* 4/1987 Shirasaka ..... 600/455  
4,667,679 A 5/1987 Sahota  
4,692,148 A 9/1987 Kantrowitz et al.  
4,706,681 A 11/1987 Breyer et al.  
4,790,831 A 12/1988 Skribiski  
4,849,172 A 7/1989 Yafuso et al.  
4,856,529 A 8/1989 Segal  
4,896,677 A 1/1990 Kaneko et al.  
4,966,148 A 10/1990 Millar  
4,967,753 A 11/1990 Haase et al.  
4,979,510 A 12/1990 Franz et al.  
5,038,789 A 8/1991 Frazin et al.  
5,046,497 A 9/1991 Millar  
5,047,930 A 9/1991 Martens et al.  
5,058,597 A 10/1991 Onoda et al.  
5,078,148 A 1/1992 Nassi et al.  
5,078,678 A 1/1992 Katims  
5,105,818 A 4/1992 Christian et al.  
5,107,841 A 4/1992 Sturgill  
5,125,410 A 6/1992 Misono et al.  
5,174,295 A 12/1992 Christian et al.  
5,190,045 A 3/1993 Frazin  
5,207,226 A 5/1993 Bailin et al.  
5,220,924 A 6/1993 Frazin  
5,226,421 A \* 7/1993 Frisbie et al. .... 600/453  
5,269,289 A 12/1993 Takehana et al.  
5,271,404 A 12/1993 Corl et al.  
5,311,871 A 5/1994 Yock  
5,421,338 A 6/1995 Crowley et al.  
5,431,628 A \* 7/1995 Millar ..... 604/100.01  
5,477,858 A 12/1995 Norris et al.  
5,492,125 A 2/1996 Kim et al.  
5,546,949 A 8/1996 Frazin et al.  
5,566,674 A 10/1996 Weng  
5,575,286 A 11/1996 Weng et al.  
5,588,432 A 12/1996 Crowley  
5,640,961 A 6/1997 Verdonk  
5,657,760 A 8/1997 Ying et al.  
5,666,958 A 9/1997 Rothenberg et al.  
5,669,389 A 9/1997 Rotteveel et al.  
5,693,032 A 12/1997 Bierman  
5,697,377 A 12/1997 Wittkamp et al.  
5,709,210 A \* 1/1998 Green et al. .... 600/453  
5,722,959 A 3/1998 Bierman  
5,733,323 A 3/1998 Buck et al.  
5,749,364 A 5/1998 Sliwa et al.  
5,782,766 A 7/1998 Weng et al.  
5,785,657 A 7/1998 Breyer et al.  
5,795,298 A 8/1998 Vesely et al.  
5,803,083 A 9/1998 Buck et al.  
5,836,882 A 11/1998 Frazin  
5,857,973 A 1/1999 Ma et al.  
5,860,951 A 1/1999 Eggers et al.  
5,876,342 A 3/1999 Chen et al.  
5,878,746 A 3/1999 Lemelson et al.  
5,891,036 A 4/1999 Izumi  
5,897,488 A 4/1999 Ueda  
5,908,385 A 6/1999 Chechelski et al.  
5,935,143 A 8/1999 Hood  
5,938,603 A 8/1999 Ponzi  
5,999,846 A 12/1999 Pardey et al.  
6,007,491 A 12/1999 Ling et al.  
6,059,731 A 5/2000 Seward et al.  
6,083,170 A 7/2000 Ben-Haim  
6,120,445 A 9/2000 Grunwald  
6,179,781 B1 1/2001 Phillips  
6,179,782 B1 1/2001 Cuce  
6,213,947 B1 4/2001 Phillips  
6,251,073 B1 6/2001 Imran et al.  
6,264,611 B1 7/2001 Ishikawa et al.  
6,364,838 B1 4/2002 Freiburger et al.  
6,500,130 B2 12/2002 Kinsella et al.  
6,520,916 B1 2/2003 Brennen  
6,542,626 B1 4/2003 Brouwer et al.  
6,551,244 B1 4/2003 Gee  
6,556,695 B1 4/2003 Packer et al.

(56)

## References Cited

## U.S. PATENT DOCUMENTS

6,561,979 B1 5/2003 Wood et al.  
 6,591,144 B2 7/2003 Pigott  
 6,594,524 B2 7/2003 Esteller et al.  
 6,612,992 B1 9/2003 Hossack et al.  
 6,638,243 B2 10/2003 Kupiecki  
 6,685,648 B2 2/2004 Flaherty et al.  
 6,689,119 B1 2/2004 Di Caprio et al.  
 6,695,785 B2 2/2004 Brisken et al.  
 6,704,590 B2 3/2004 Haldeman  
 6,719,756 B1 4/2004 Muntermann  
 6,733,454 B1 5/2004 Bakircioglu et al.  
 6,740,590 B1 5/2004 Yano et al.  
 6,749,606 B2 6/2004 Keast et al.  
 6,814,702 B2 11/2004 Redano  
 6,866,677 B2 3/2005 Douk et al.  
 6,896,658 B2 5/2005 Ji et al.  
 6,931,269 B2 8/2005 Terry  
 6,973,352 B1 12/2005 Tsutsui et al.  
 7,037,290 B2 5/2006 Gardeski et al.  
 7,043,293 B1 5/2006 Baura  
 7,150,716 B2 12/2006 Jones et al.  
 7,200,435 B2 4/2007 Ricci et al.  
 7,204,798 B2 4/2007 Zdeblick et al.  
 7,225,013 B2 5/2007 Geva et al.  
 7,346,393 B2 3/2008 Spinelli et al.  
 7,366,563 B2 4/2008 Kleen et al.  
 7,367,949 B2 5/2008 Korhonen et al.  
 7,384,411 B1 6/2008 Condado  
 7,393,501 B2 7/2008 Zumeris et al.  
 7,422,563 B2 9/2008 Roschak et al.  
 7,433,853 B2 10/2008 Brockway et al.  
 7,479,141 B2 1/2009 Kleen et al.  
 7,485,095 B2 2/2009 Shusterman  
 7,599,730 B2 10/2009 Hunter et al.  
 7,627,386 B2 12/2009 Mo et al.  
 7,640,055 B2 12/2009 Geva et al.  
 7,668,579 B2 2/2010 Lynn  
 7,697,972 B2 4/2010 Verard et al.  
 7,708,696 B2 5/2010 Ritter et al.  
 7,733,224 B2 6/2010 Tran  
 7,794,407 B2 9/2010 Rothenberg  
 7,833,221 B2 11/2010 Voegelé et al.  
 7,966,061 B2 6/2011 Al-Abed et al.  
 7,981,038 B2 7/2011 Kanade et al.  
 7,991,458 B2 8/2011 Hardahl et al.  
 7,996,061 B2 8/2011 Mollard et al.  
 8,046,052 B2 10/2011 Verard et al.  
 8,052,648 B2 11/2011 Dikeman et al.  
 8,060,185 B2 11/2011 Hunter et al.  
 8,208,989 B2 6/2012 Maschke et al.  
 8,409,103 B2 4/2013 Grunwald et al.  
 8,645,962 B2 2/2014 Kono et al.  
 8,965,490 B2 2/2015 Lee et al.  
 2002/0010461 A1 1/2002 KenKnight et al.  
 2002/0045810 A1 4/2002 Ben-Haim  
 2002/0087156 A1 7/2002 Maguire et al.  
 2002/0111548 A1 8/2002 Swanson et al.  
 2002/0151790 A1 10/2002 Abend  
 2002/0156363 A1 10/2002 Hunter et al.  
 2002/0168618 A1\* 11/2002 Anderson et al. .... 434/262  
 2002/0188257 A1 12/2002 Bierman  
 2003/0083717 A1 5/2003 Mlynski et al.  
 2003/0109785 A1 6/2003 Buck et al.  
 2003/0111548 A1 6/2003 Buck  
 2003/0204187 A1\* 10/2003 Hintringer et al. .... 606/41  
 2003/0220568 A1 11/2003 Hansmann et al.  
 2004/0011358 A1 1/2004 Smaldone et al.  
 2004/0039436 A1 2/2004 Spenser et al.  
 2004/0102719 A1 5/2004 Keith et al.  
 2004/0116809 A1 6/2004 Chow et al.  
 2004/0116969 A1 6/2004 Owen et al.  
 2004/0158143 A1 8/2004 Flaherty et al.  
 2004/0225215 A1 11/2004 Querleux et al.  
 2004/0254523 A1 12/2004 Fitzgerald et al.  
 2005/0085718 A1 4/2005 Shahidi

2005/0148836 A1 7/2005 Kleen et al.  
 2005/0159738 A1 7/2005 Visram et al.  
 2006/0079868 A1 4/2006 Makin et al.  
 2006/0084883 A1 4/2006 Linker  
 2006/0094923 A1 5/2006 Mate  
 2007/0016068 A1 1/2007 Grunwald et al.  
 2007/0016069 A1 1/2007 Grunwald et al.  
 2007/0016070 A1 1/2007 Grunwald et al.  
 2007/0016072 A1 1/2007 Grunwald et al.  
 2007/0167738 A1 7/2007 Timinger et al.  
 2007/0265526 A1 11/2007 Govari et al.  
 2007/0276334 A1 11/2007 Bierman et al.  
 2008/0058607 A1 3/2008 Watrous  
 2008/0161669 A1 7/2008 Hauck et al.  
 2008/0188740 A1 8/2008 Diaz et al.  
 2009/0005675 A1 1/2009 Grunwald et al.  
 2009/0118612 A1 5/2009 Grunwald et al.  
 2009/0143740 A1 6/2009 Bierman et al.  
 2009/0156926 A1 6/2009 Messerly et al.  
 2009/0177090 A1 7/2009 Grunwald et al.  
 2009/0182283 A1 7/2009 Sloan  
 2009/0234328 A1 9/2009 Cox et al.  
 2009/0259124 A1 10/2009 Rothenberg  
 2009/0262977 A1 10/2009 Huang et al.  
 2009/0287070 A1 11/2009 Baker, Jr.  
 2009/0287191 A1 11/2009 Ferren et al.  
 2010/0036227 A1 2/2010 Cox et al.  
 2010/0204569 A1 8/2010 Burnside et al.  
 2011/0257600 A1 10/2011 Kessler  
 2012/0035434 A1 2/2012 Ferren et al.  
 2012/0136242 A1 5/2012 Qi et al.  
 2013/0289417 A1 10/2013 Grunwald et al.  
 2013/0296693 A1 11/2013 Wenzel et al.  
 2013/0296725 A1 11/2013 Lee et al.

## FOREIGN PATENT DOCUMENTS

CN 1899222 A 1/2007  
 DE 4319033 C1 6/1994  
 EP 0238791 A2 9/1987  
 EP 0917069 A1 5/1999  
 EP 1181895 A2 2/2002  
 EP 1393674 A1 3/2004  
 EP 1509866 B1 1/2012  
 JP 62500703 A 3/1987  
 JP 62-236532 10/1987  
 JP 3205040 A 9/1991  
 JP 4017843 1/1992  
 JP 4501972 A 4/1992  
 JP U-7-3608 1/1995  
 JP H07505791 A1 6/1995  
 JP 08-229044 9/1995  
 JP 09-253084 9/1997  
 JP 10-277039 10/1998  
 JP 2000514320 T 10/2000  
 JP 2004500210 1/2004  
 JP 2004130114 4/2004  
 JP 2005152654 A 6/2005  
 JP 2006513731 4/2006  
 KR 1020090019762 2/2009  
 WO WO8602540 A1 5/1986  
 WO WO9104707 A1 4/1991  
 WO WO9308738 A1 5/1993  
 WO WO98/08440 A1 3/1998  
 WO WO9927994 A1 6/1999  
 WO WO 01/70303 A2 9/2001  
 WO WO0174249 A1 10/2001  
 WO WO2006/051523 A2 5/2006  
 WO WO2007017771 A2 2/2007  
 WO WO 2007/047360 A2 4/2007  
 WO WO2007082093 A2 7/2007

## OTHER PUBLICATIONS

Hellerstein et al.; Recording of intracavity potentials through a single lumen, saline filled cardiac catheter; P.S.E.B.M., vol. 71; pp. 58-60; 1949.

(56)

**References Cited**

**OTHER PUBLICATIONS**

Naylor; Reduction of malposition in peripherally inserted central catheters with tip location system; JAVA; vol. 12; No. 1; pp. 29-31; 2007.

Pittiruti et al.; The EKG method for positioning the tip of PICCs; results from two preliminary studies; JAVA; vol. 13; No. 4; pp. 112-119; 2008.

Stas et al.; Peroperative intravascular electrographic control of catheter tip position in access ports placed by venous cut-down technique; EJSO; vol. 27; pp. 316-320; 2001.

Bidoggia et al.; Transseptal left heart catheterization: usefulness of the intracavitary electrocardiogram in the localization of the fossa ovalis; Catheterization and Cardiovascular Diagnosis; New York, NY; vol. 24; No. 3; pp. 221-225; Nov. 1, 1991.

Benchimol et al.; Right atrium and superior vena cava flow velocity in man measured with the doppler-catheter flowmeter-telemetry system; The Amer. J of Med.; vol. 48; pp. 303-309; 1970.

Benchimol et al.; Bidirectional blood flow velocity in the cardiac chambers and great vessels studied with the doppler ultrasonic flowmeter; The Amer. J of Med.; vol. 52; pp. 467-473; 1972.

Kalmanson et al.; Letter to the Editor; "Directional vs bidirectional doppler velocimeter"; Am. Heart J.; vol. 83; No. 3; pp. 437; Mar. 1972.

Lewis et al.; A Study of Normal and abnormal femoral venous flow velocity using a directional doppler; Br. J. Surg; vol. 59, No. 4; pp. 303; Apr. 1972.

Radke et al.; Control of the placement of a central venous catheter using doppler ultrasound; Der Anaesthesist May 1990; vol. 39; No. 5; pp. 283-287; May 1990.

Brunner, Eberhard; Ultrasound system considerations and their impact on front-end components; Analog Devices, Inc.; pp. 1-19; May-Jun. 2002.

Fearon et al.; Evaluating intermediate coronary lesions in the cardiac catheterization laboratory; Rev Cardiovasc Med; vol. 4; No. 1; pp. 1-7; 2003.

McGee, et al.; Accurate placement of central venous catheters: A prospective, randomized, multicenter trial; Critical Care Medicine, vol. 21, No. 8, pp. 1118-1123, Aug. 1993.

Schummer et al.; Central venous catheters—the inability of 'intra-atrial ECG' to prove adequate positioning; British Jour. of Anaesthesia, vol. 93, No. 2; pp. 193-198, 2004.

Starr, et al.; EKG guided placement of subclavian CVP catheters using J-wire; Ann. Surg.; vol. 204, No. 6, pp. 673-676, Dec. 1986.

\* cited by examiner

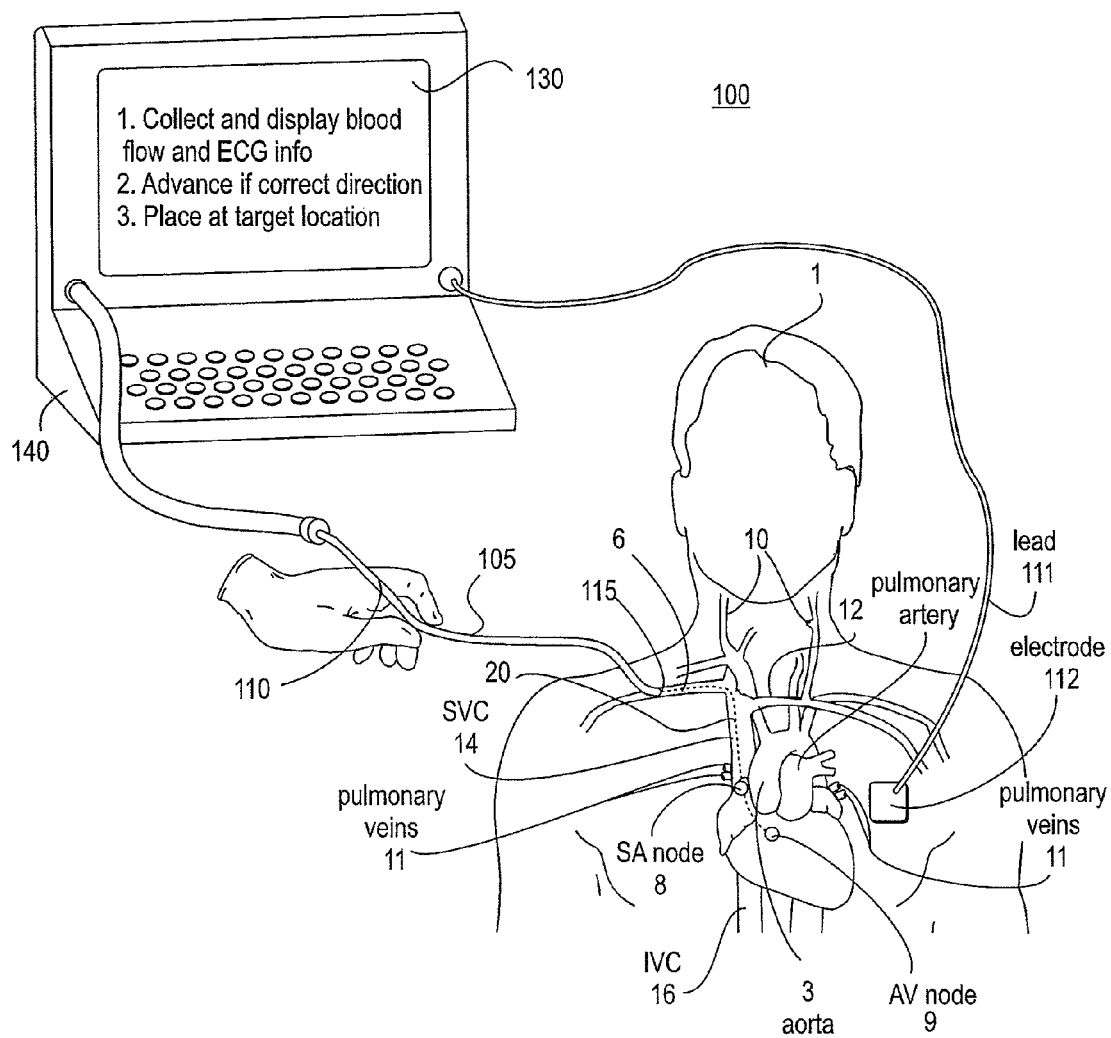


FIG. 1

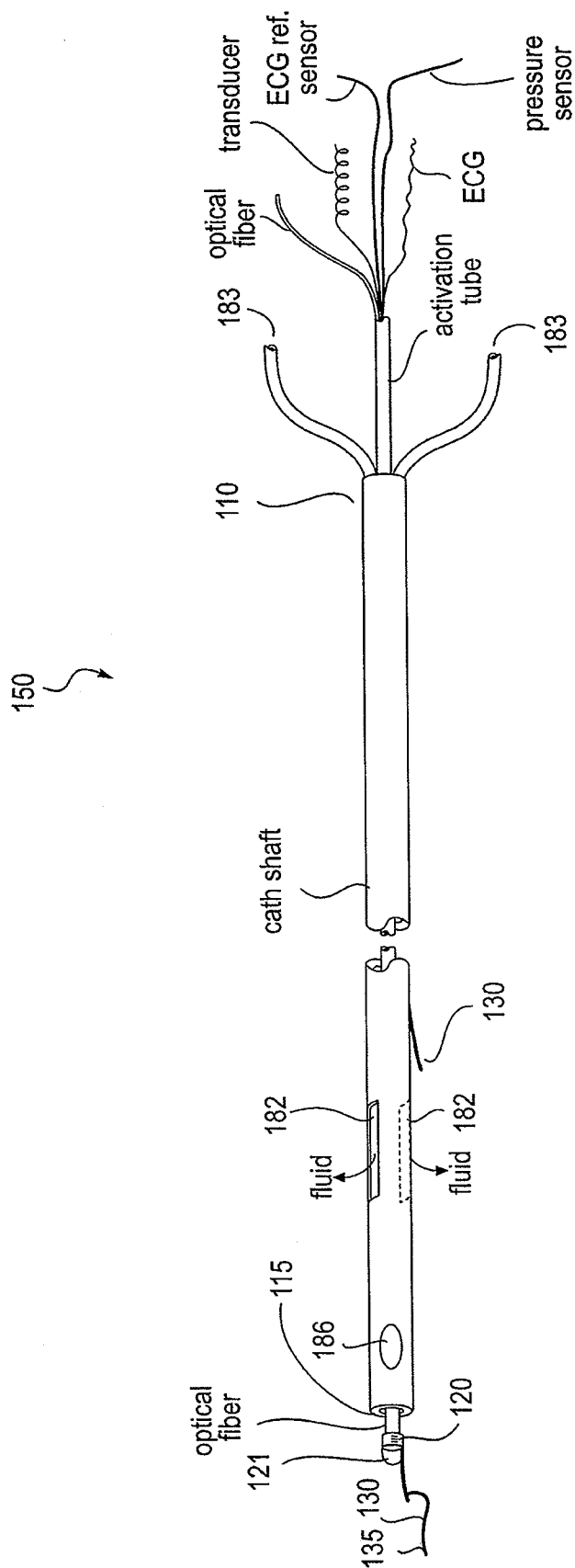
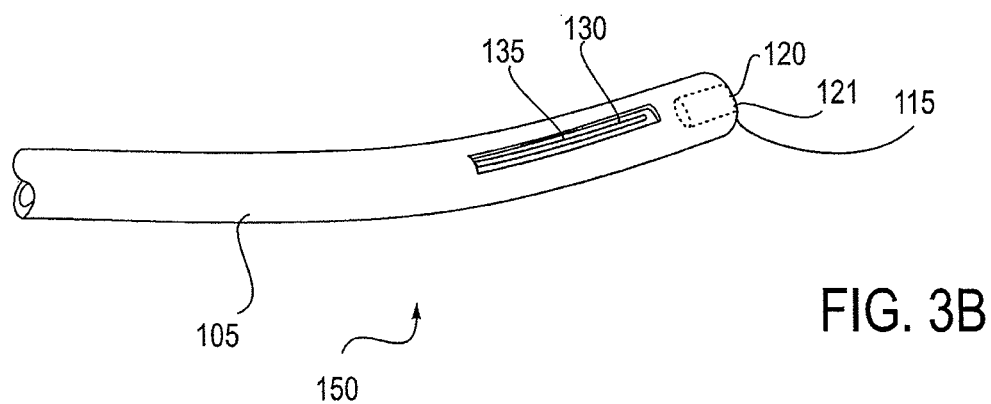
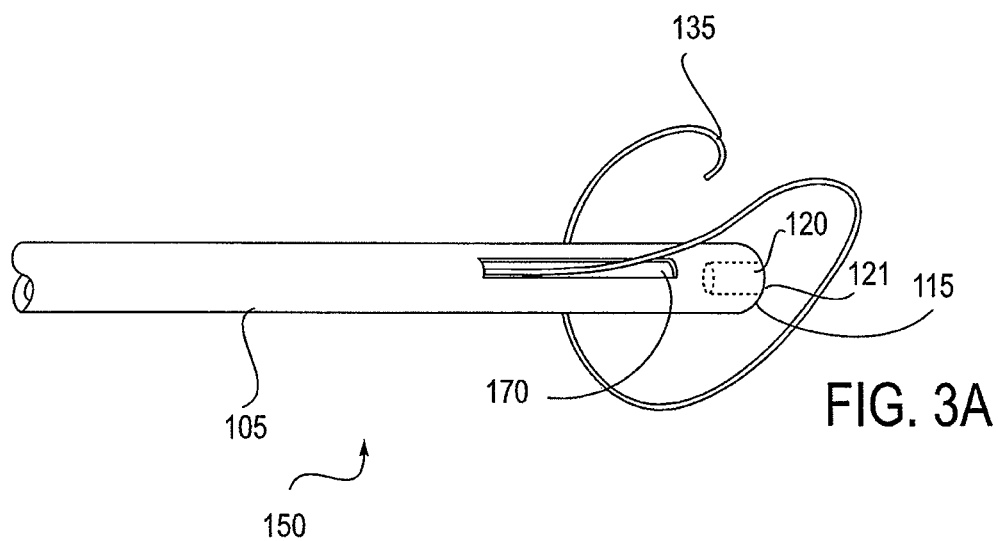
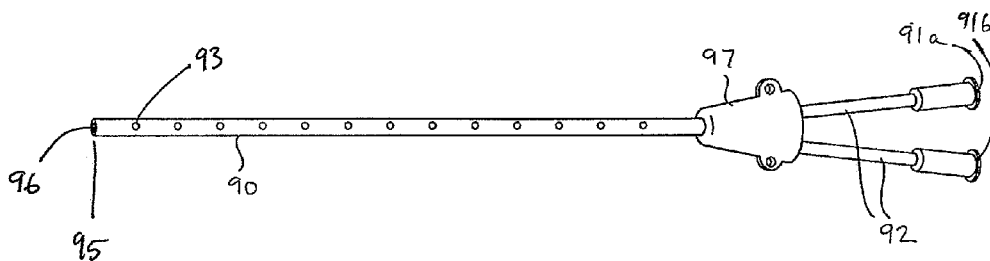
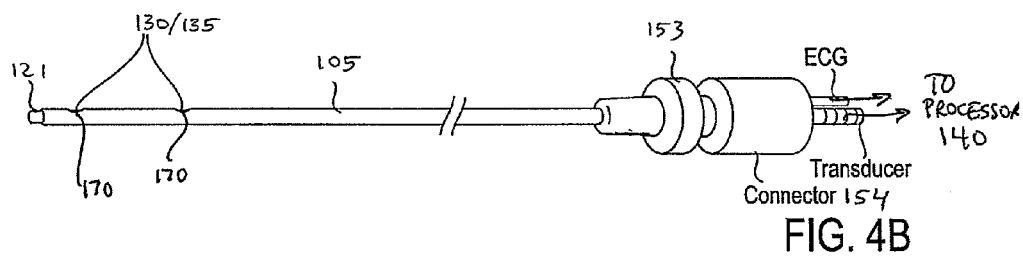
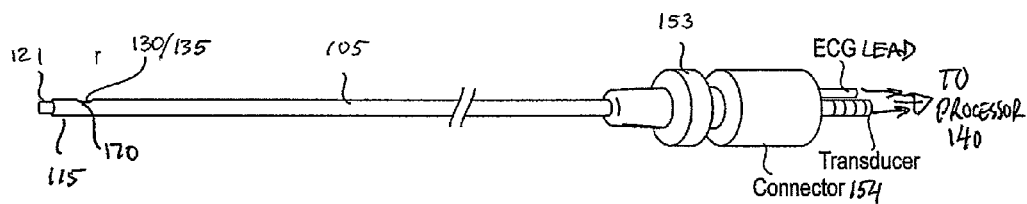


FIG. 2







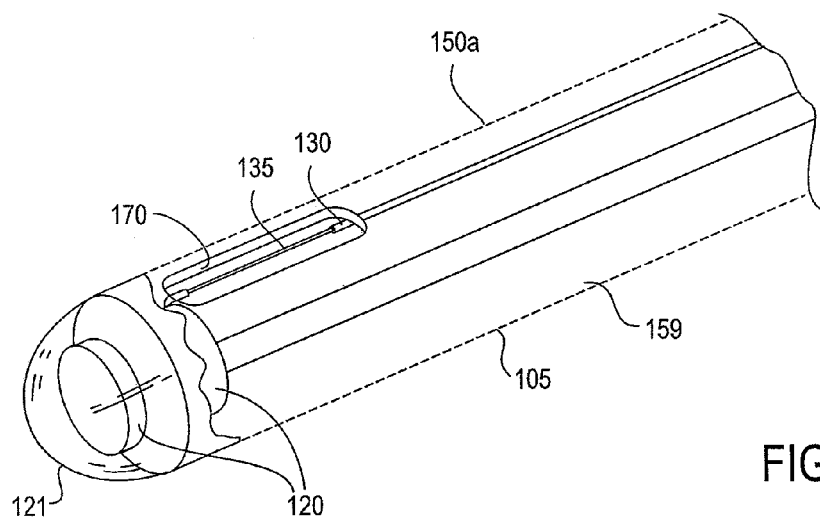


FIG. 5A

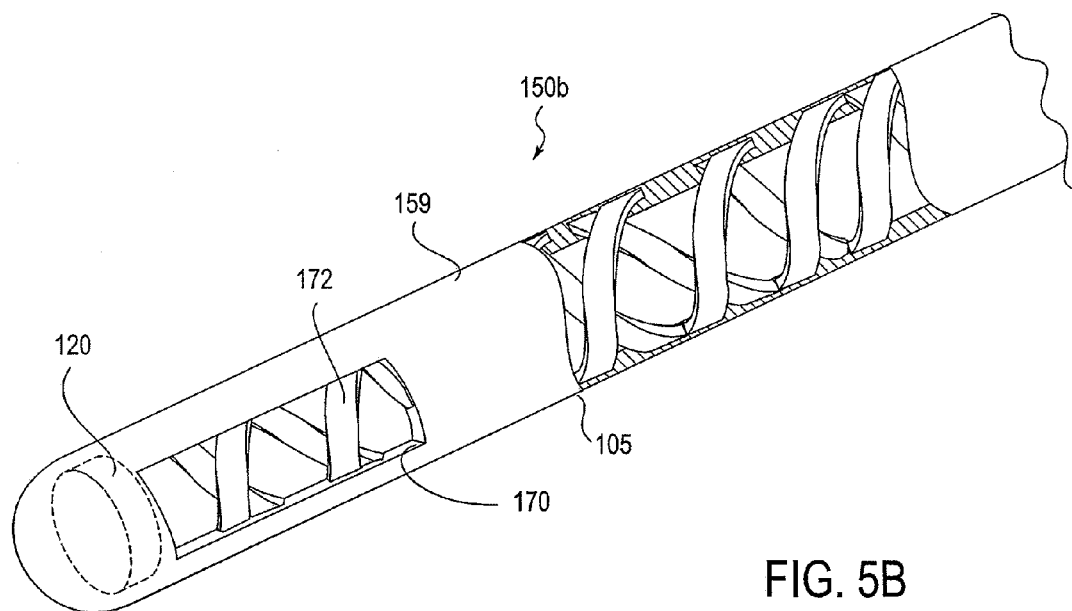


FIG. 5B

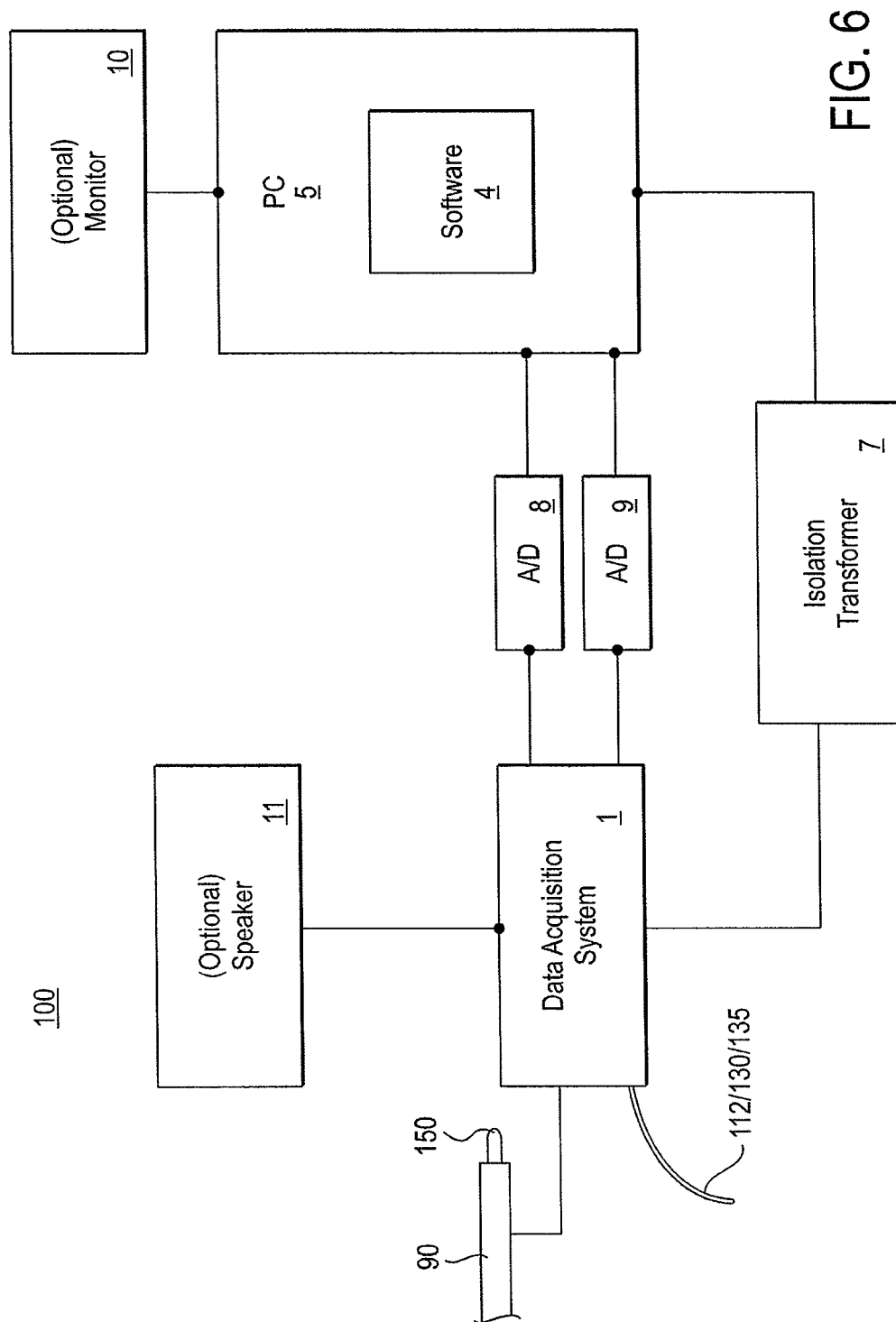


FIG. 6

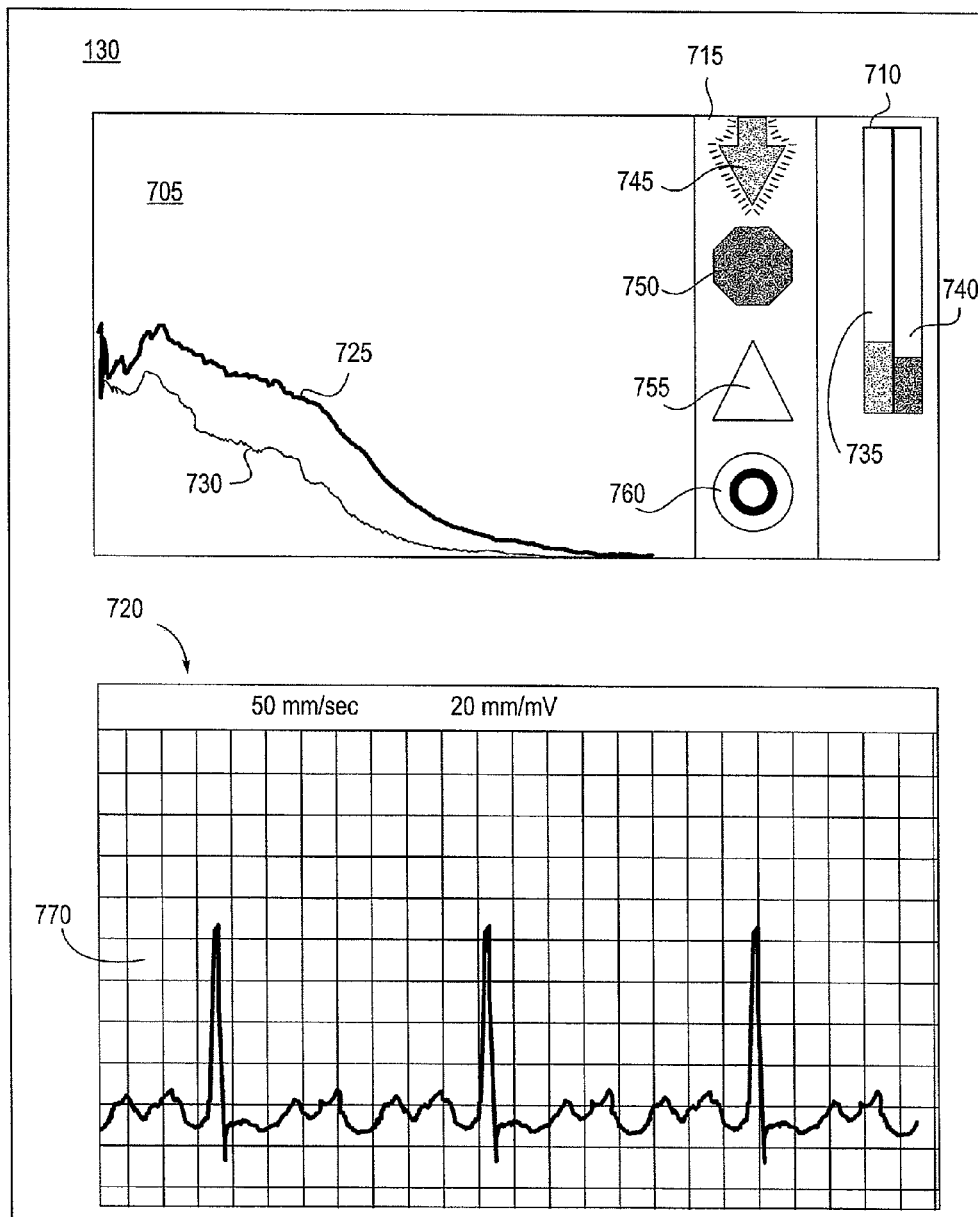


FIG. 7

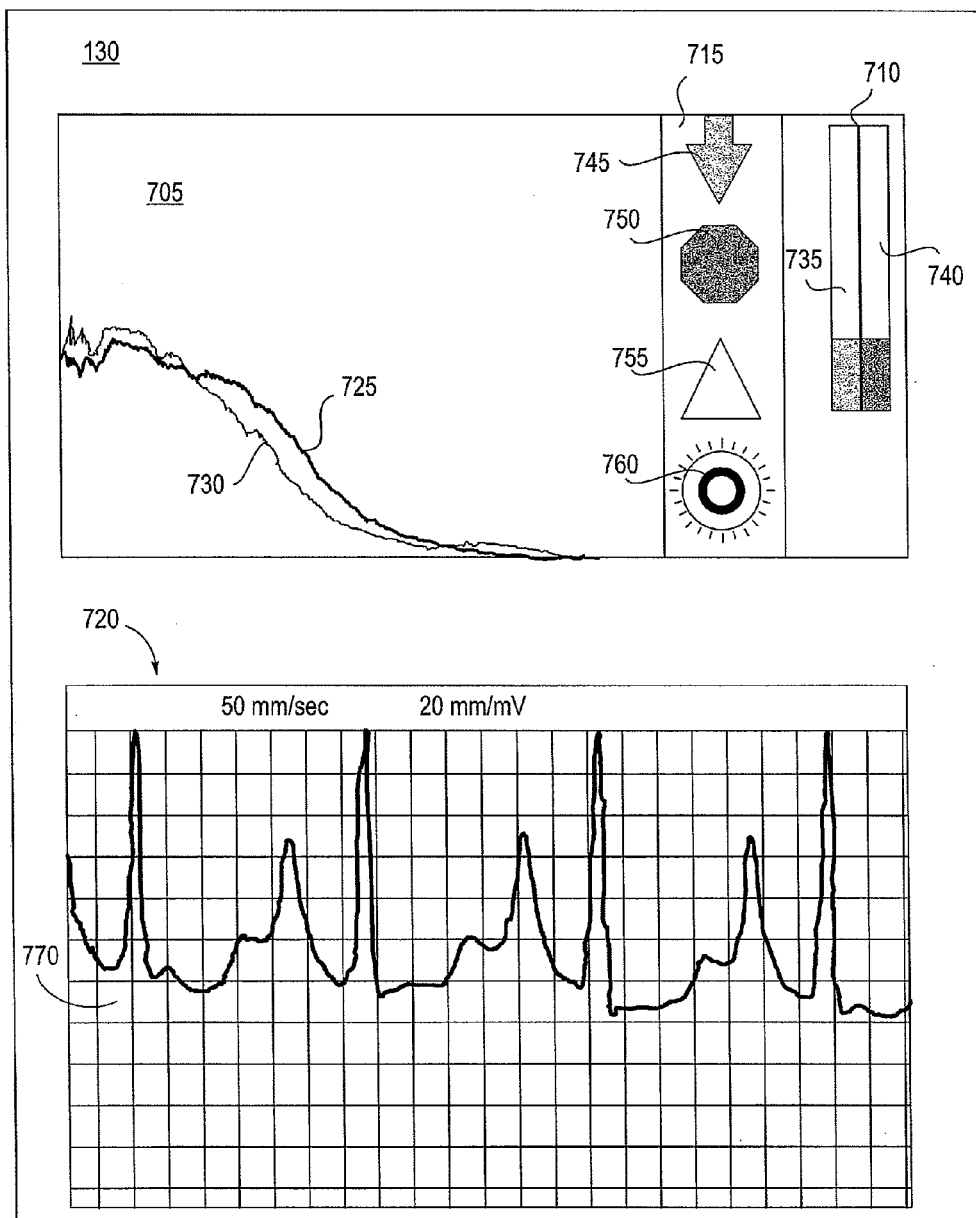


FIG. 8

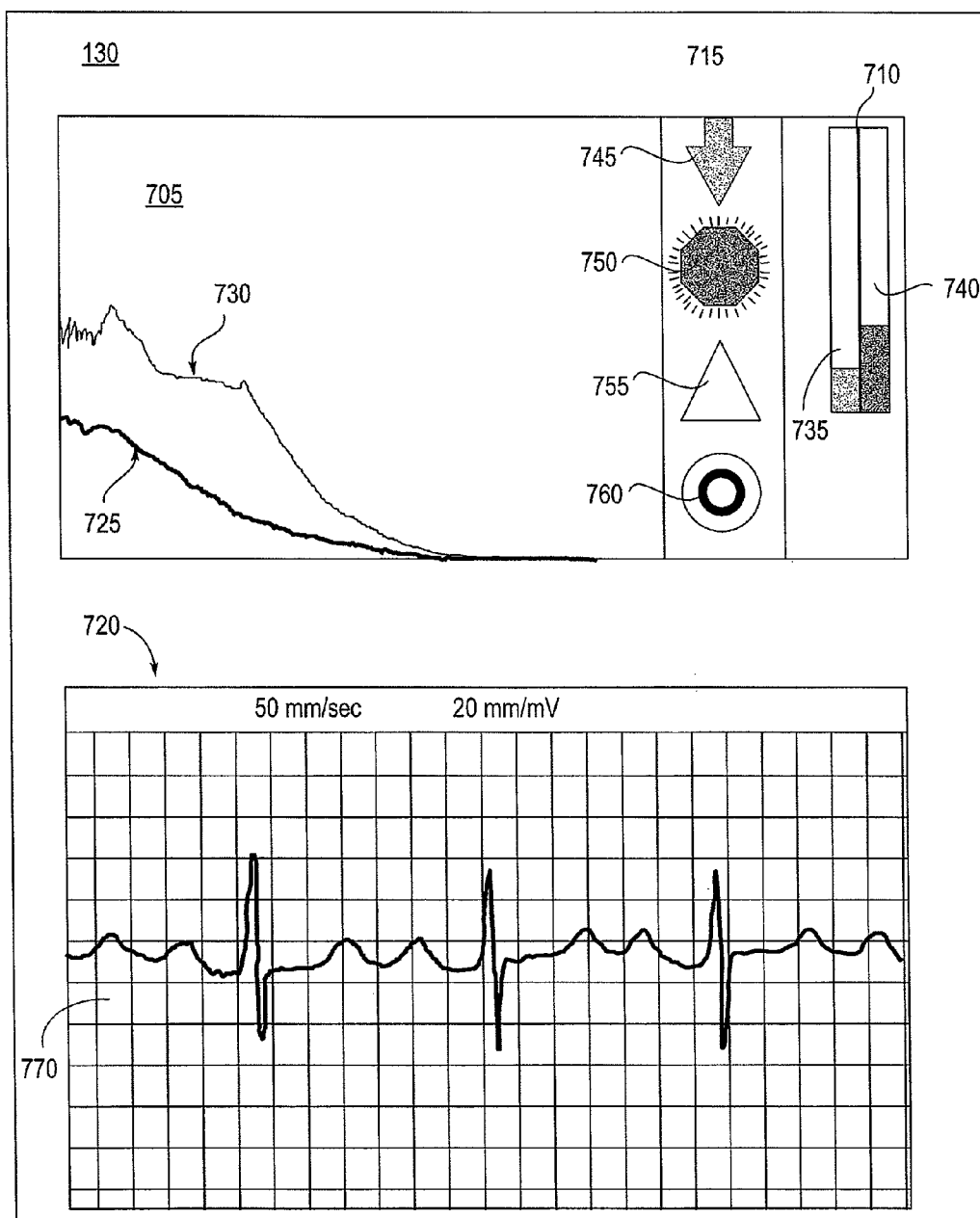
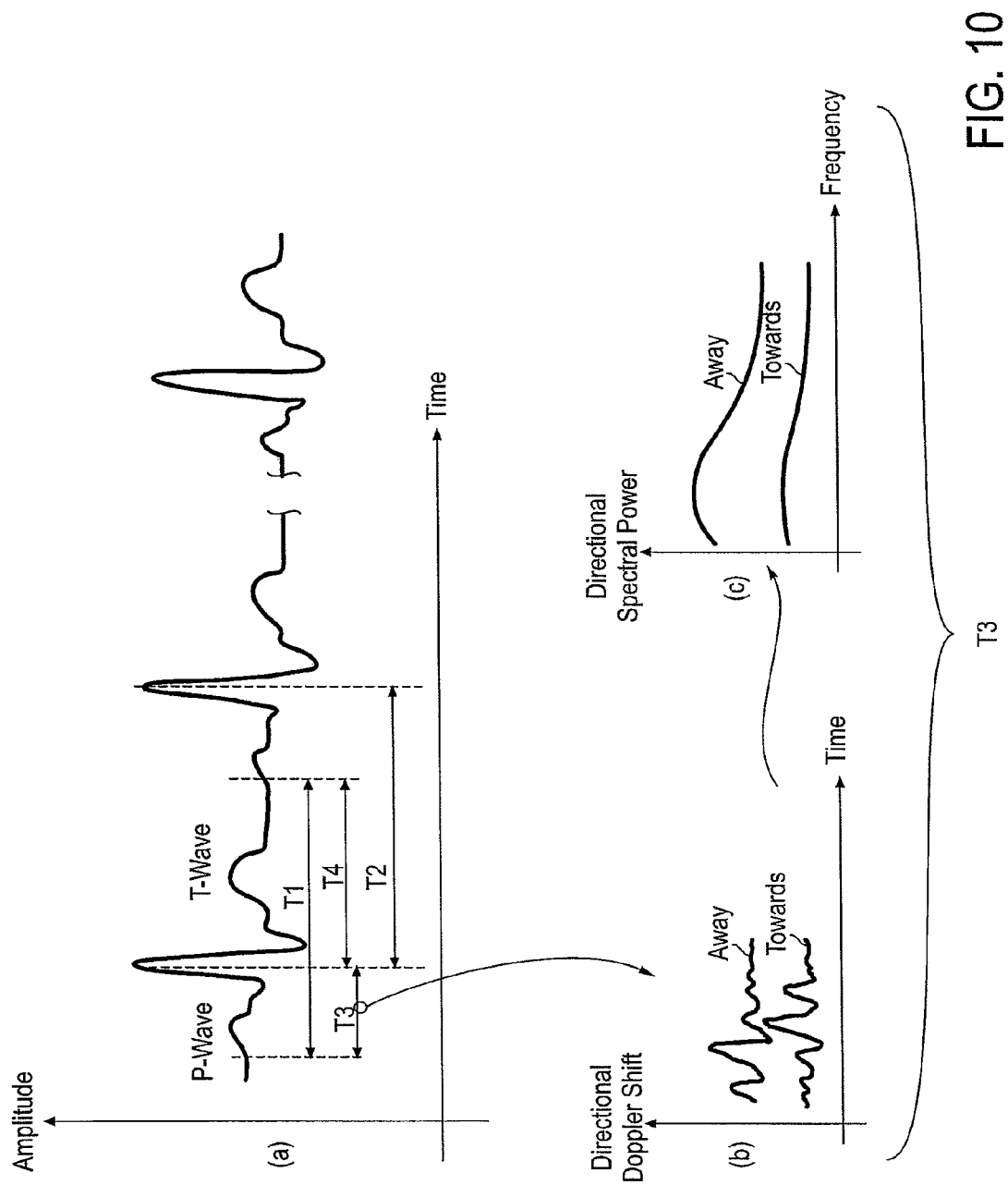


FIG. 9



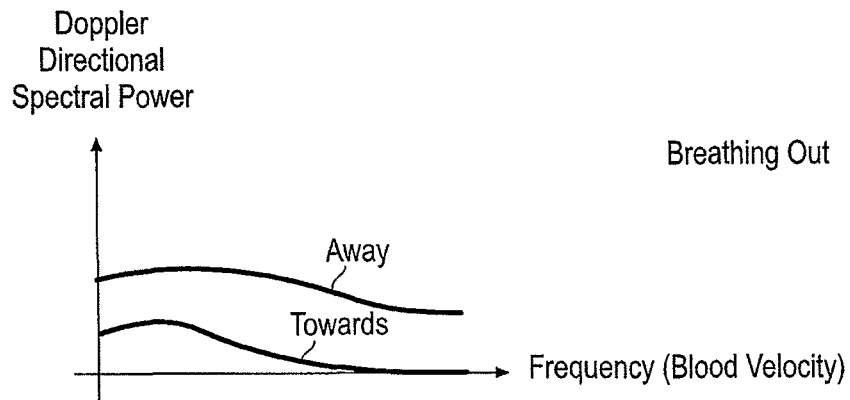
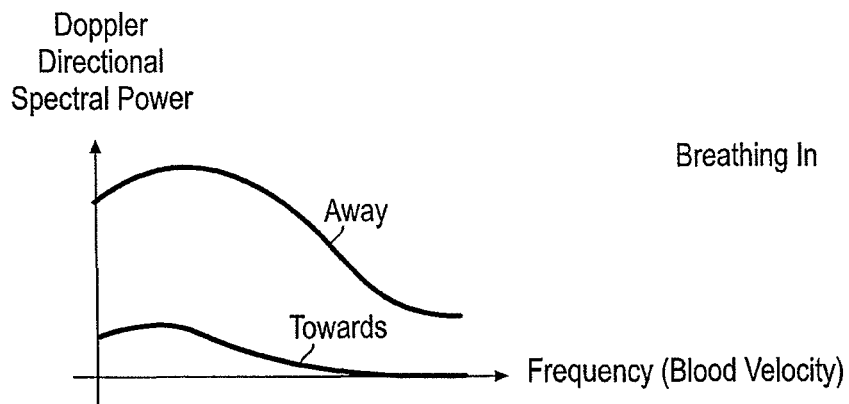
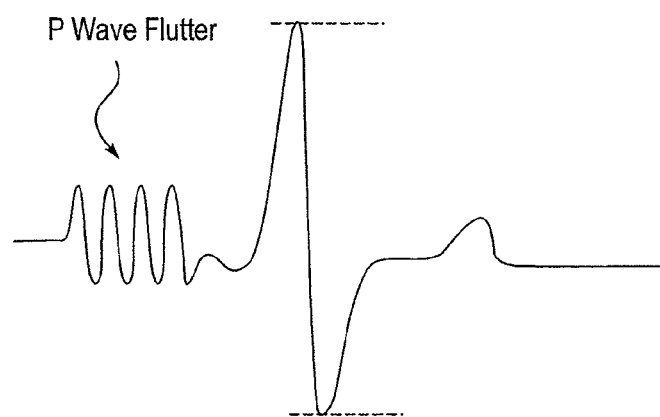
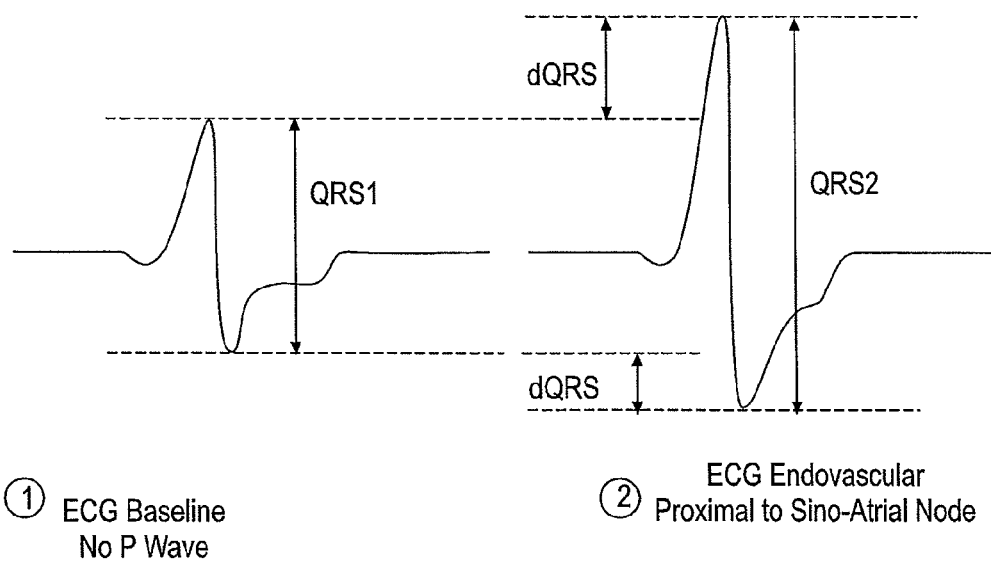


FIG. 11



③ ECG Endovascular  
Proximal to Sino-Atrial Node

FIG. 12



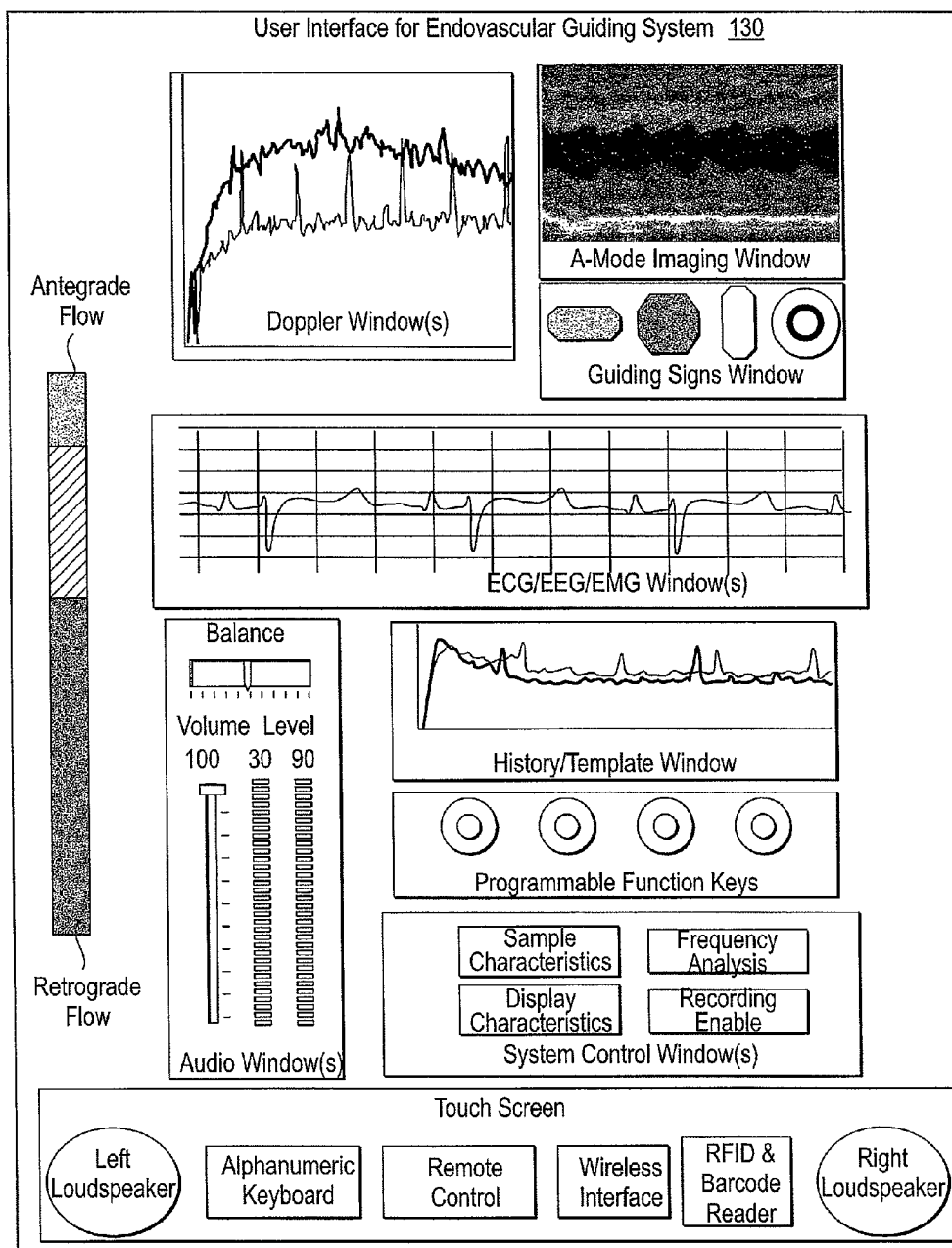


FIG. 13

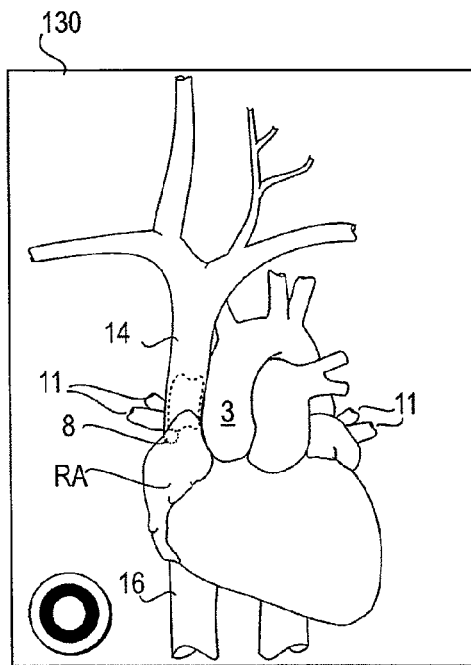


FIG. 14A

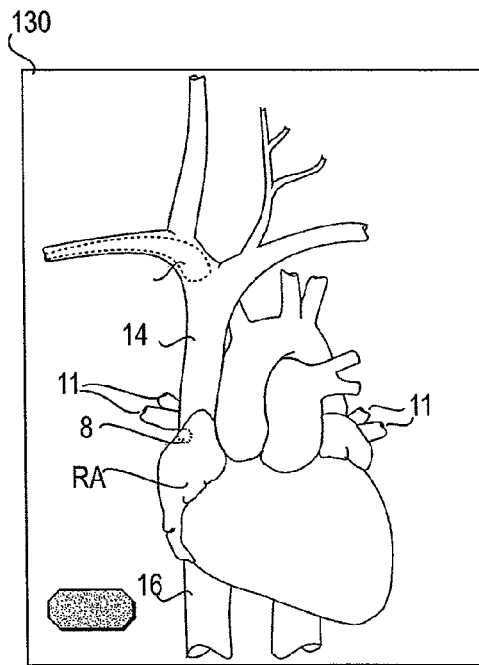


FIG. 14B

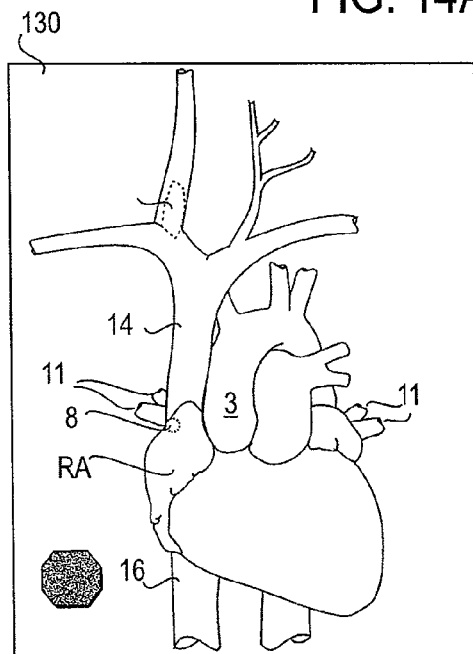


FIG. 14C

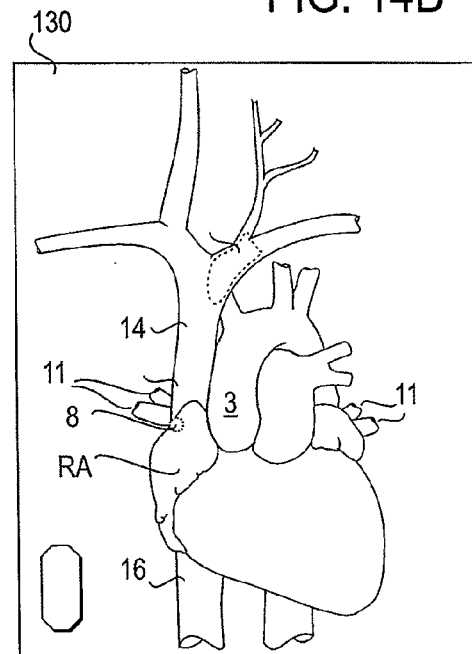


FIG. 14D

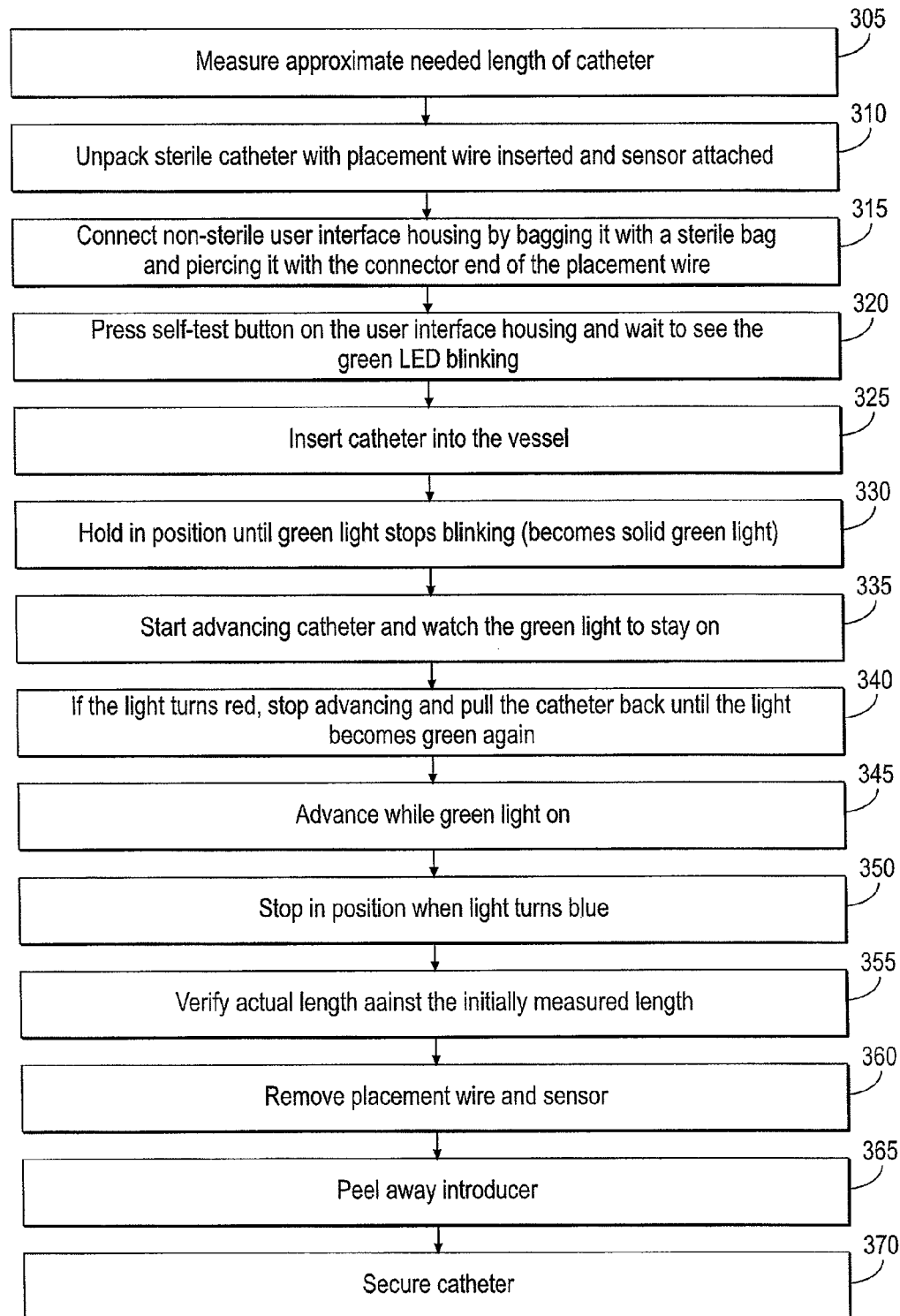


FIG. 15

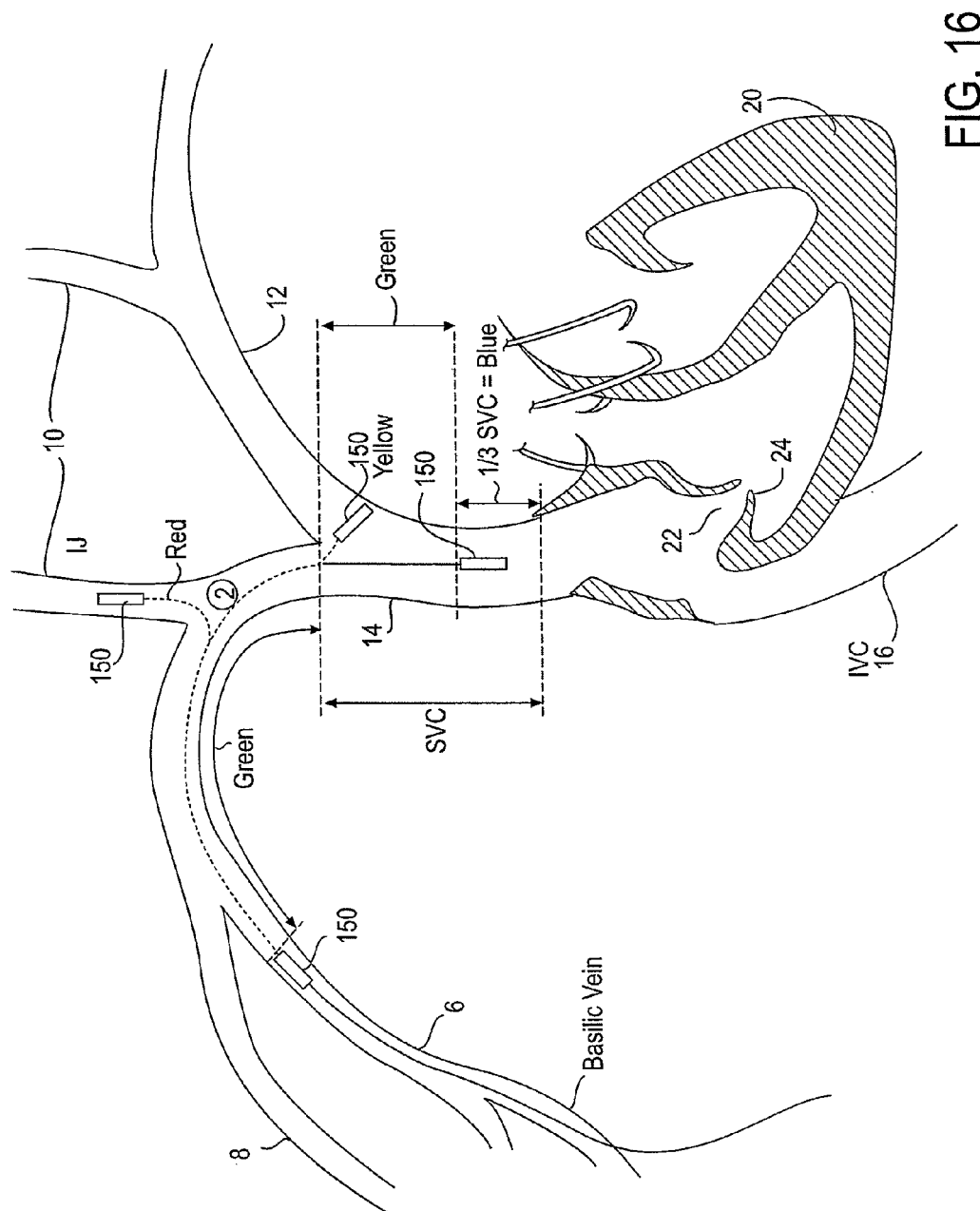


FIG. 16

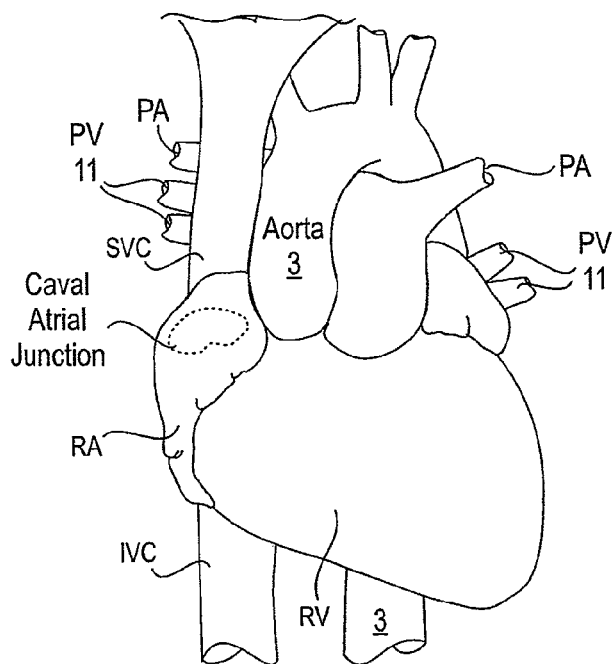


FIG. 17

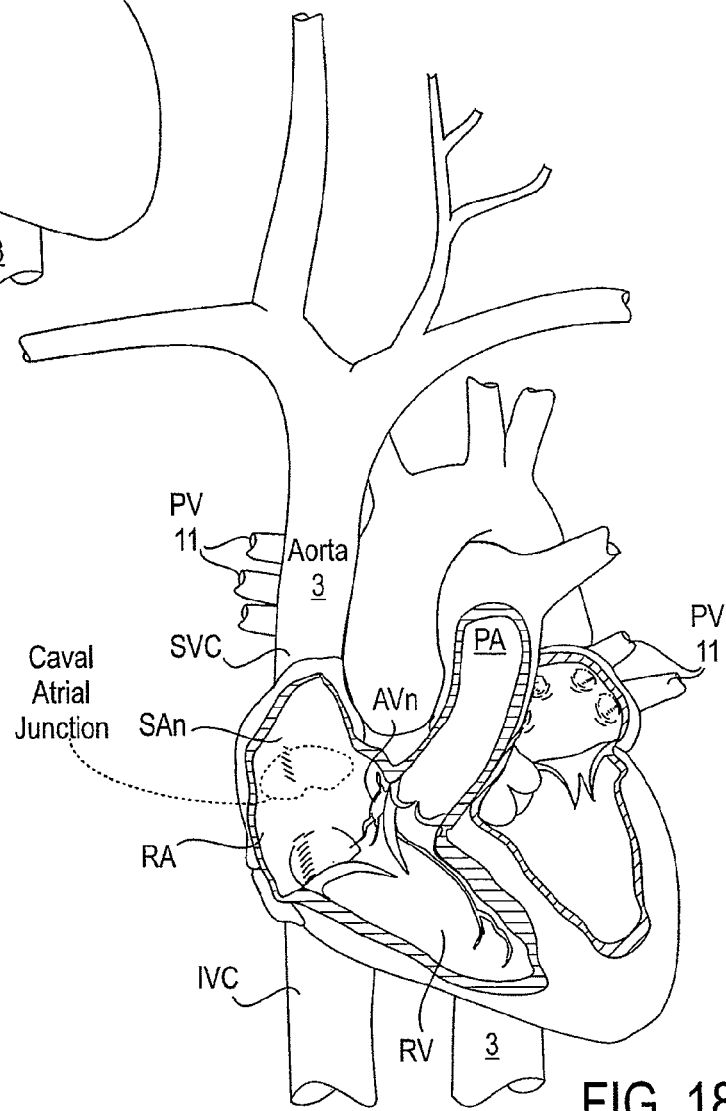
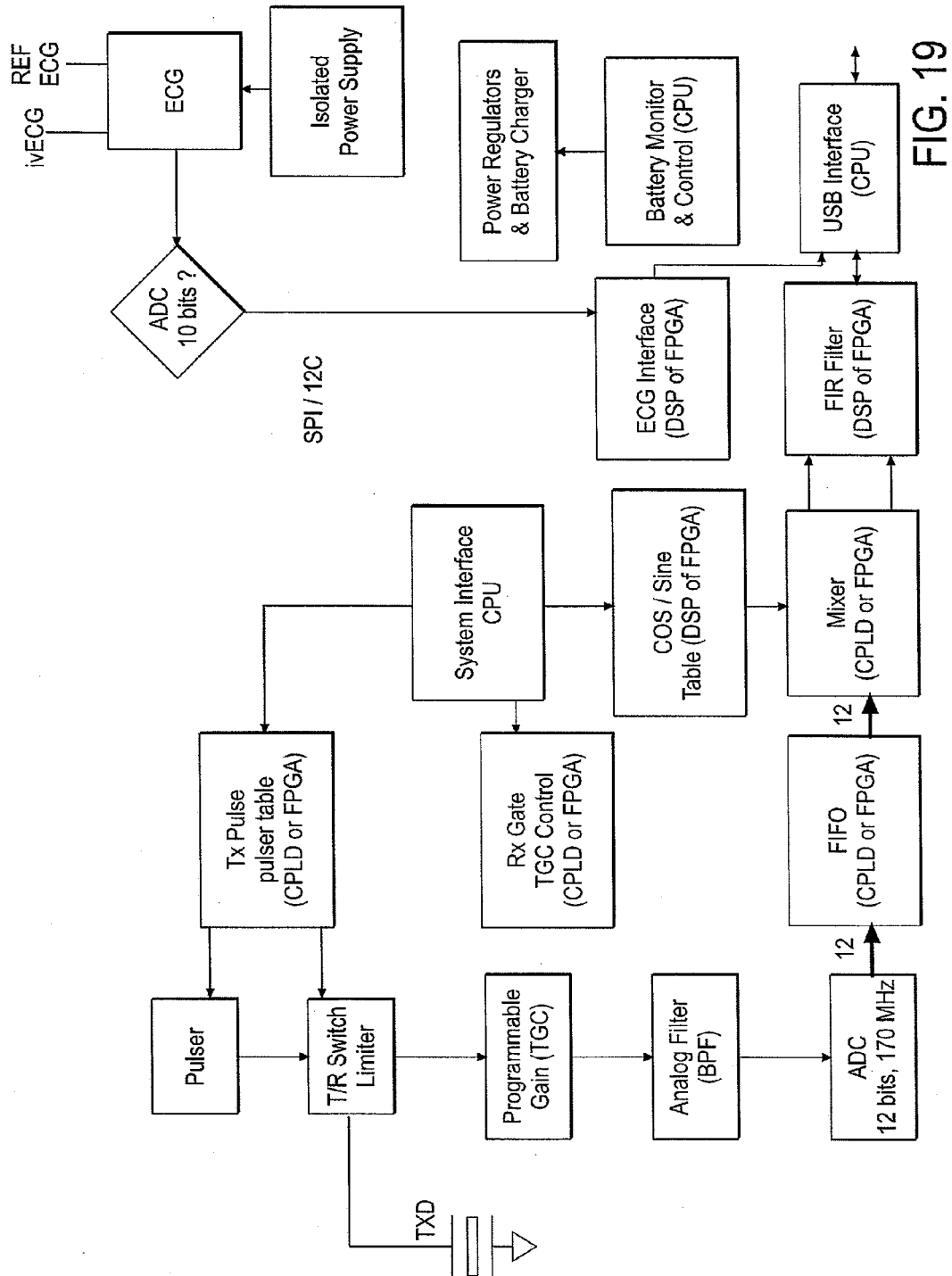


FIG. 18



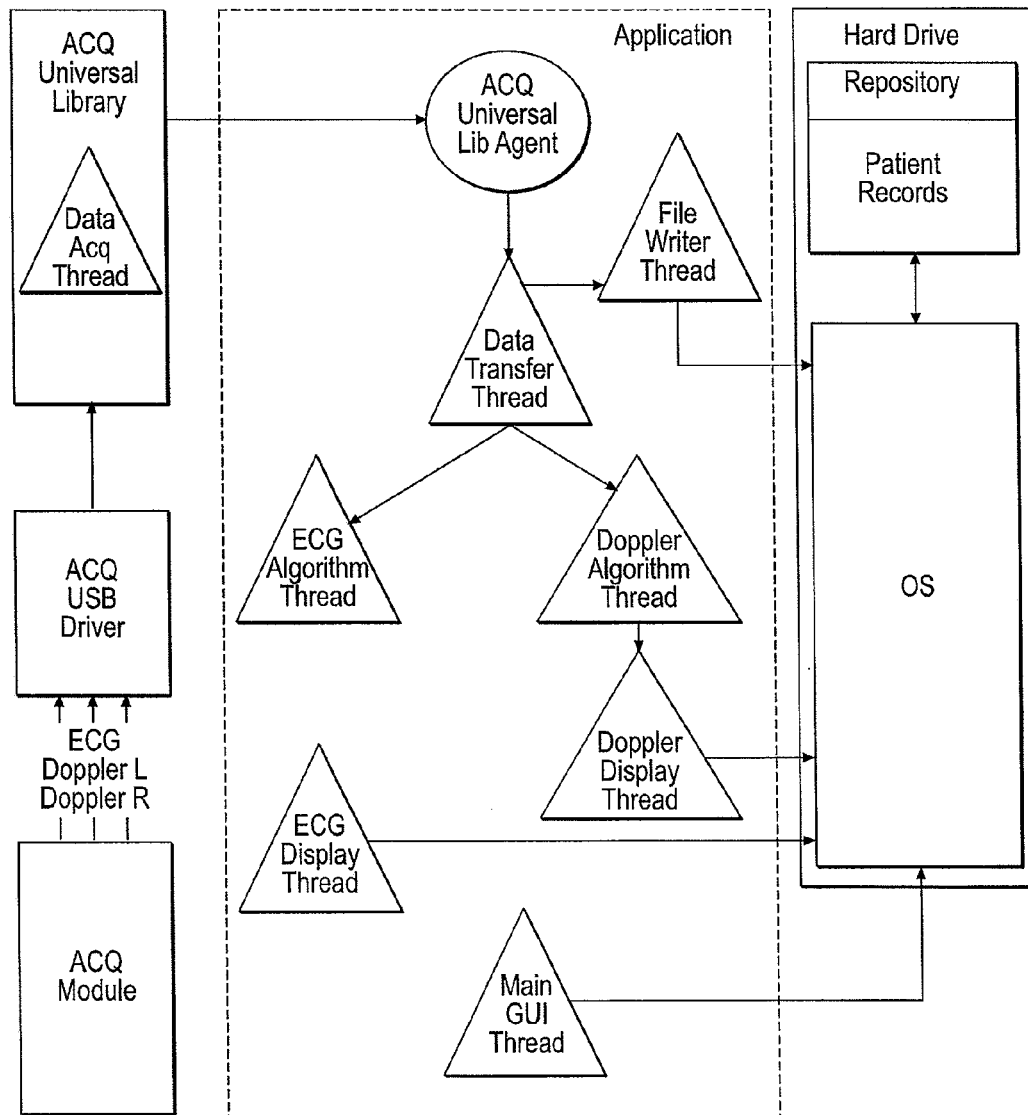


FIG. 20

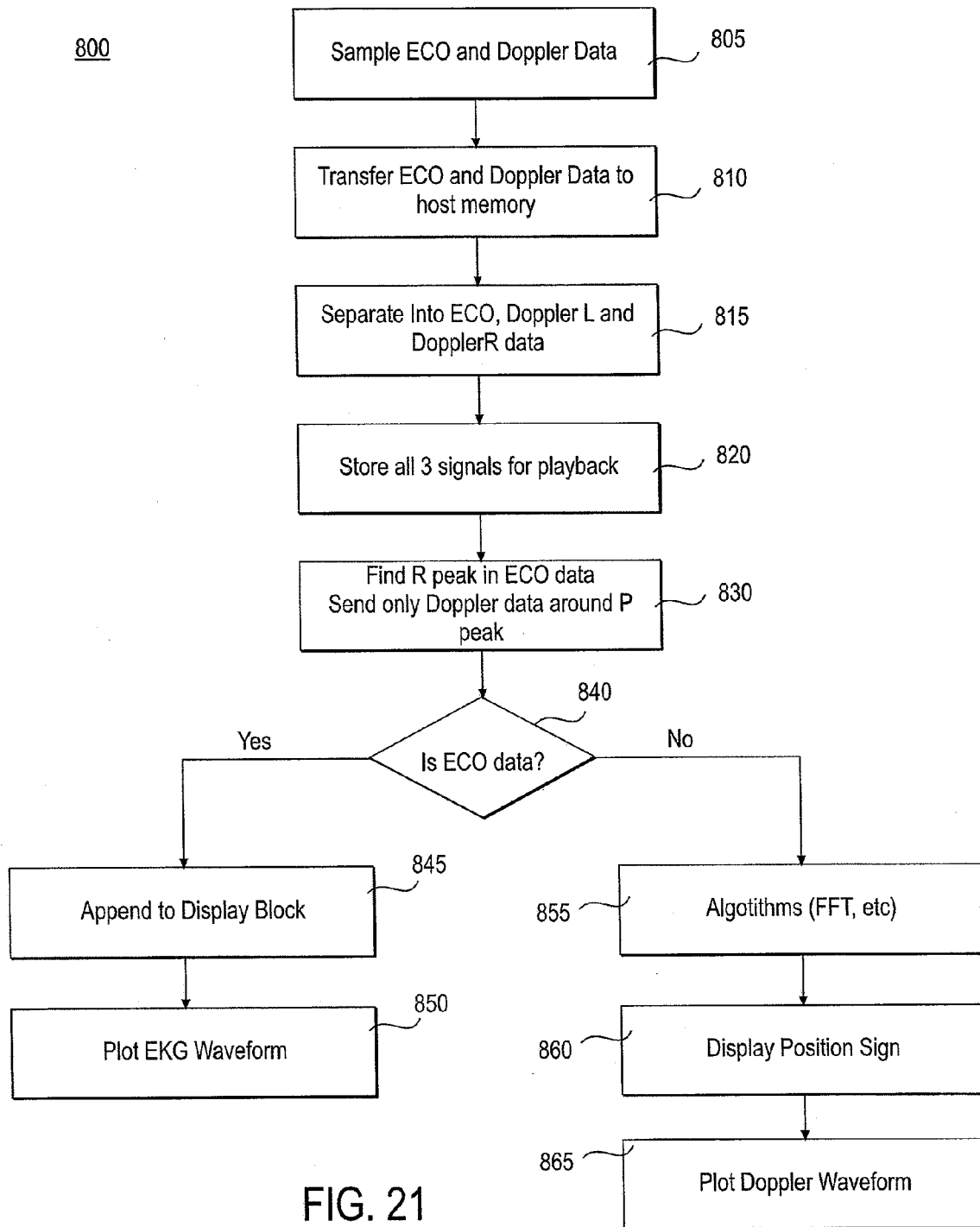
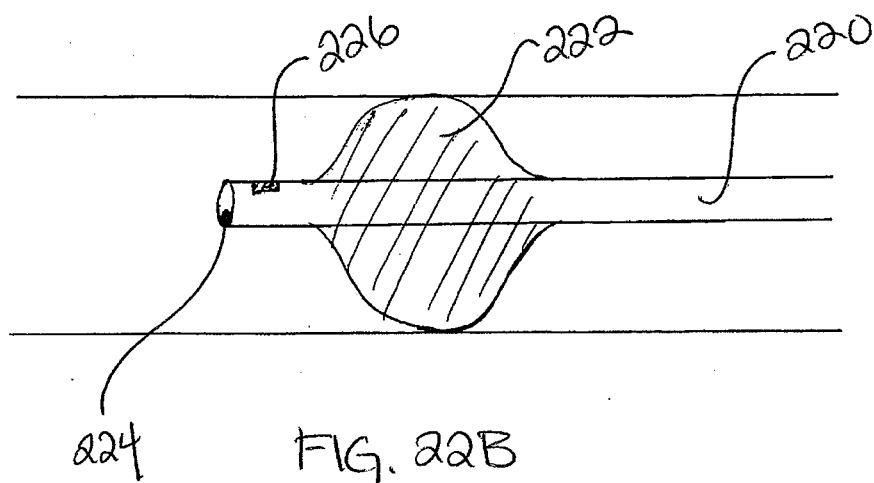
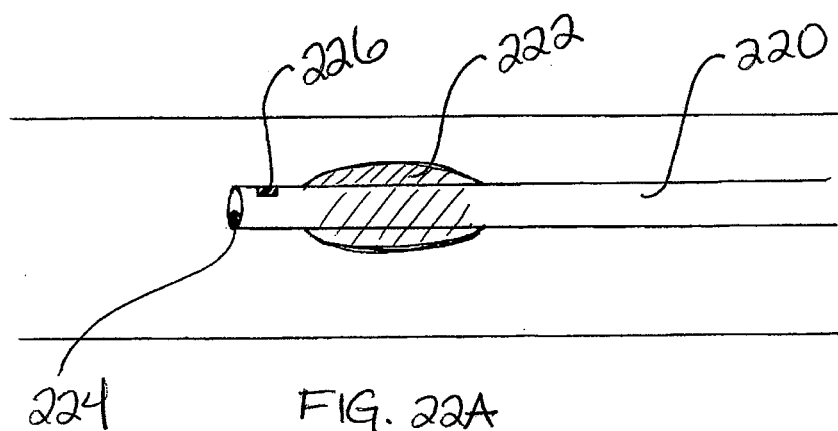


FIG. 21





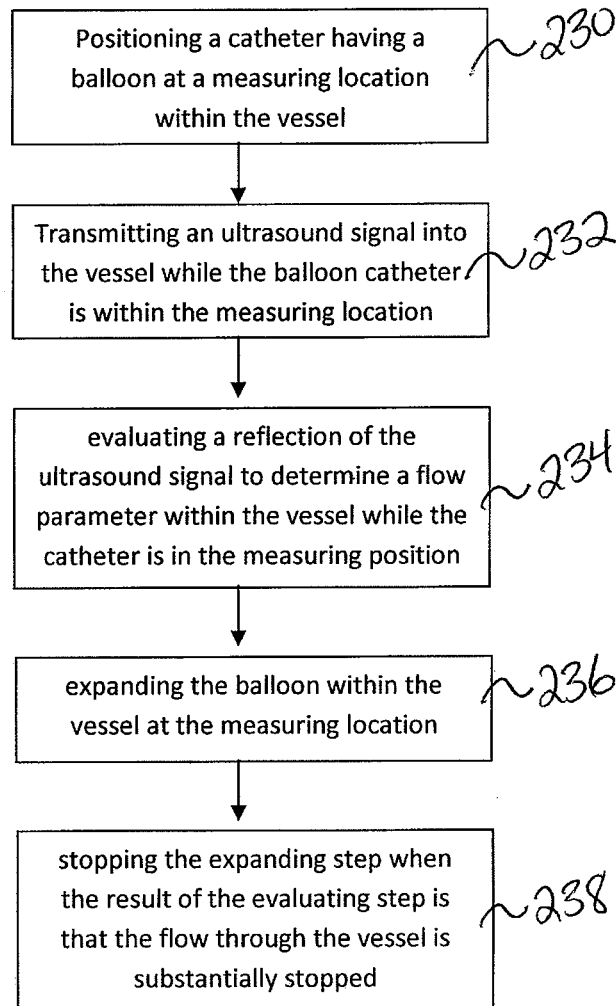


FIG. 23

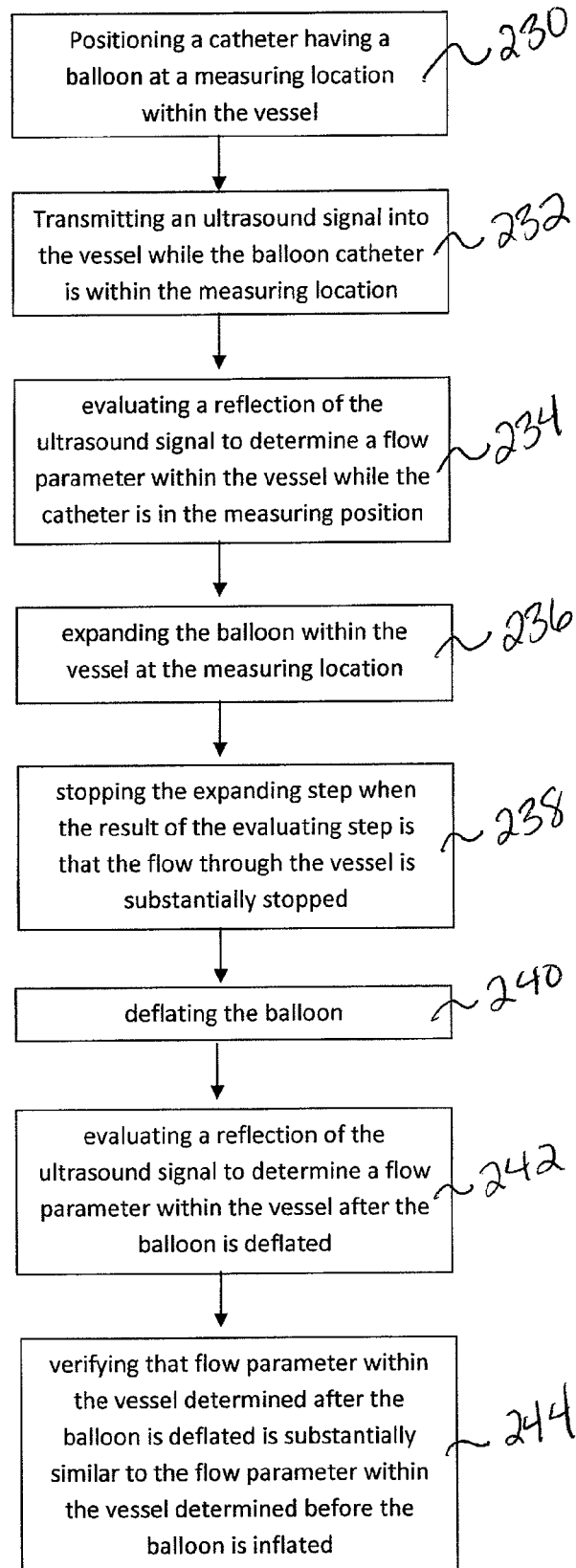


FIG. 24

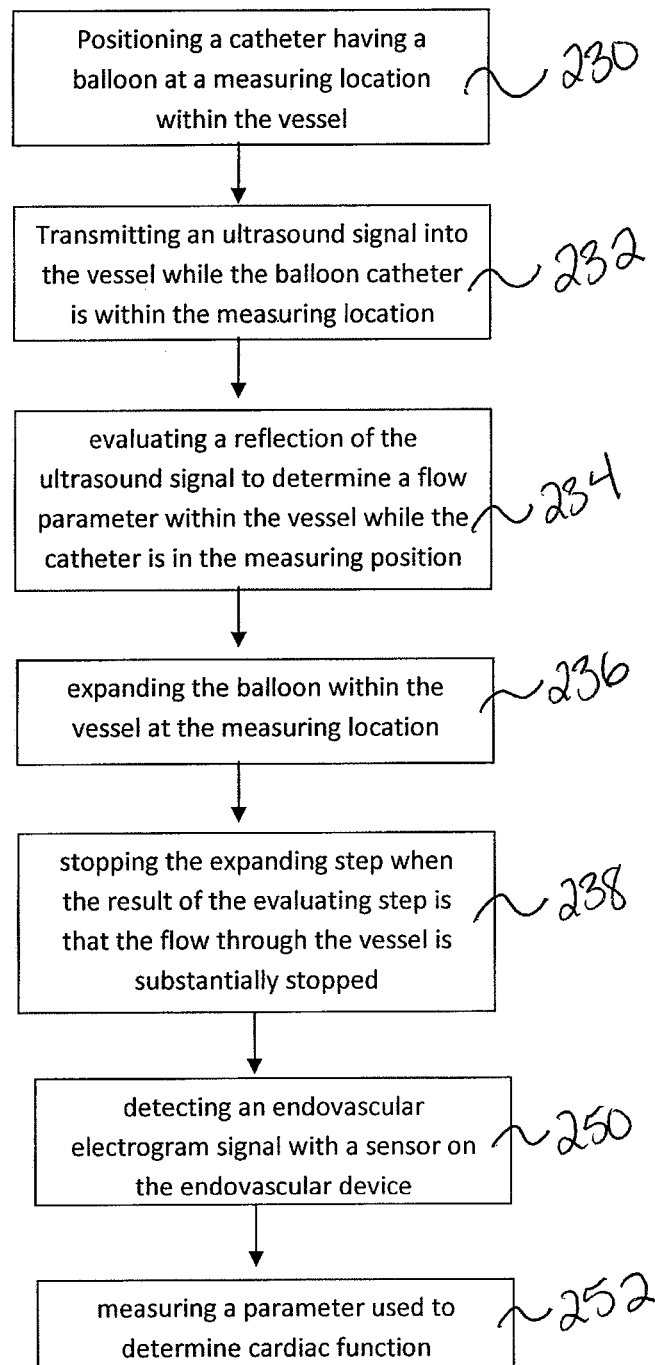


FIG. 25

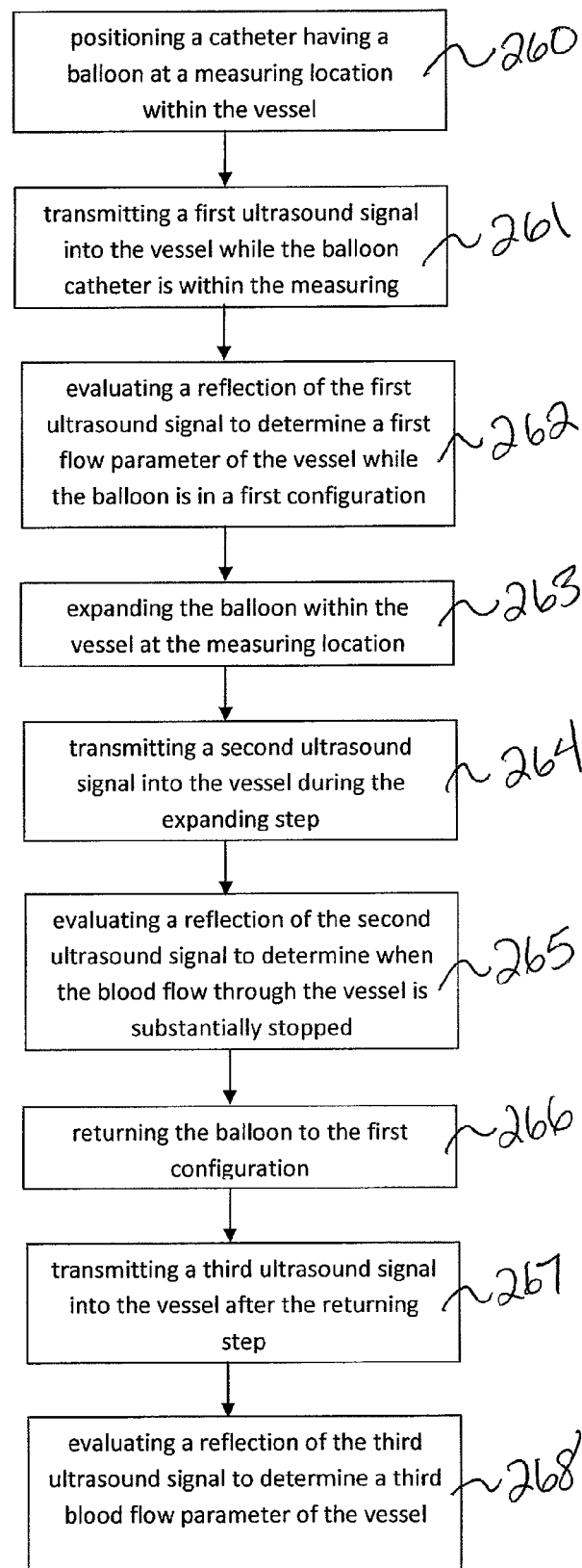


FIG. 26

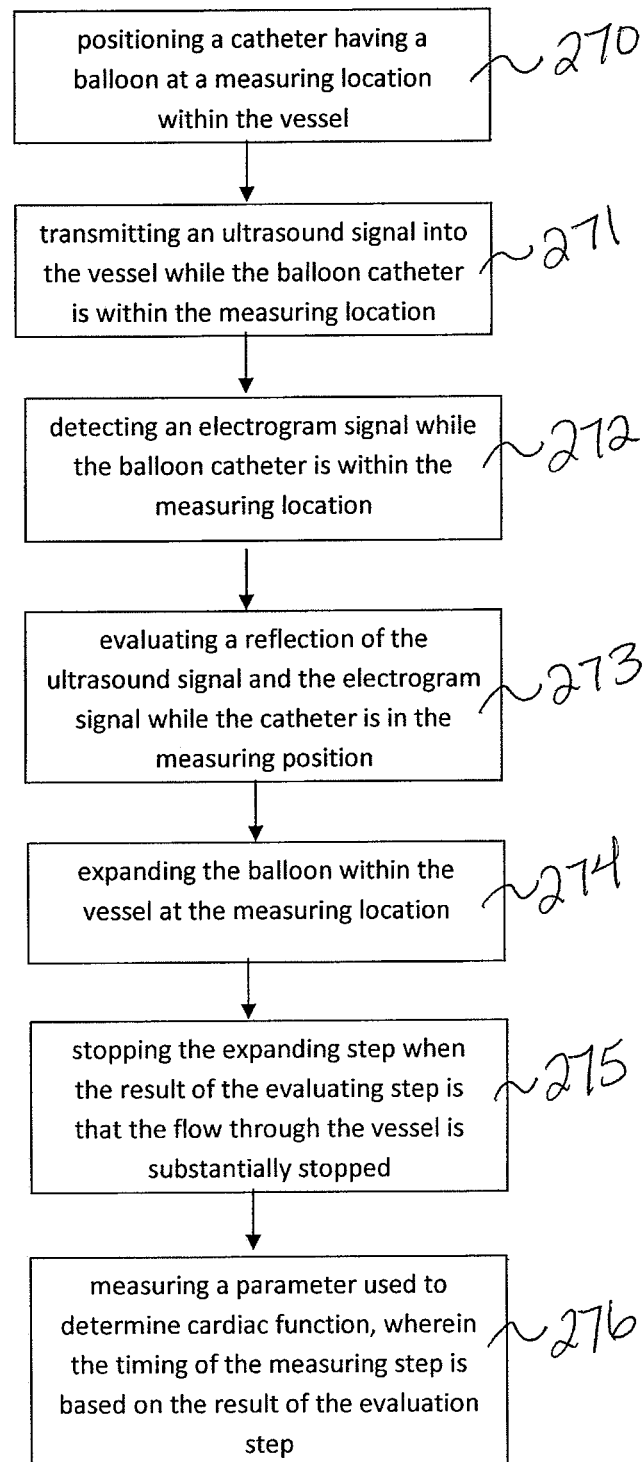


FIG. 27

## ENDOVASCULAR DEVICES AND METHODS OF USE

### CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Applications U.S. Provisional Patent Application No. 61/023,183 filed on Jan. 24, 2008 by Sorin Grunwald et al., entitled "Configurations of Guided Endovascular Access Devices", and U.S. Provisional Patent Application No. 61/023,176 filed on Jan. 24, 2008 by Sorin Grunwald et al., entitled "Endovascular Devices and Methods of Use", and U.S. Provisional Patent Application No. 61/023,179 filed on Jan. 24, 2008 by Sorin Grunwald et al., entitled "Variable Length Endovascular Devices", each of which is incorporated herein by reference in its entirety.

This application is also a continuation-in-part of U.S. Non-Provisional patent application Ser. No. 12/147,401 filed on Jun. 26, 2008 by Sorin Grunwald et al., entitled "Apparatus and Method for Endovascular Device Guiding and Positioning Using Physiological Parameters", now publication no. 2009-0005675-A1, which claims the benefit of U.S. Provisional Patent Application No. 60/937,280 filed on Jun. 26, 2007 by Sorin Grunwald et al., entitled "Apparatus and Method for Vascular Access"; U.S. Provisional Patent Application No. 60/957,316 filed on Aug. 22, 2007 by Sorin Grunwald et al., entitled "Apparatus and Method for Endovascular Guidance"; and U.S. Provisional Patent Application No. 61/023,183 filed on Jan. 24, 2008 by Sorin Grunwald et al., entitled "Configurations of Guided Endovascular Access Devices", each of which is incorporated herein by reference in their entirety.

U.S. patent application Ser. No. 12/147,401 also is a continuation-in-part of U.S. Non-Provisional patent application Ser. No. 11/431,140 filed on May 8, 2006 by Sorin Grunwald et al., entitled "Endovenous Access and Guidance System Utilizing Non-Image Based Ultrasound", now publication no. 2007-0016072-A1; U.S. Non-Provisional patent application Ser. No. 11/431,118 filed on May 8, 2006 by Sorin Grunwald et al., entitled "Endovascular Access and Guidance System Utilizing Divergent Beam Ultrasound", now publication no. 2007-0016070-A1; U.S. Non-Provisional patent application Ser. No. 11/431,093 filed on May 8, 2006 by Sorin Grunwald et al., entitled "Ultrasound Sensor", now publication no. 2007-0016069-A1; and U.S. Non-Provisional patent application Ser. No. 11/430,511 filed on May 8, 2006 by Sorin Grunwald et al., entitled "Ultrasound Methods of Positioning Guided Vascular Access Devices in the Venous System", now publication no. 2007-0016068-A1, all of which claim the benefit of U.S. Provisional patent application Ser. No. 60/678,209 filed on May 6, 2005 by Sorin Grunwald et al., entitled "Method and Apparatus for Intravascular Catheter Guiding and Positioning" and U.S. Provisional Patent Application No. 60/682,002 filed on May 18, 2005 by Sorin Grunwald et al., entitled "Method and Apparatus for Intravascular Catheter Guiding and Positioning", each of which is incorporated herein by reference in their entirety.

### BACKGROUND OF THE INVENTION

The invention relates to the guidance, positioning and placement confirmation of intravascular devices, such as catheters, stylets, guidewires and other elongate bodies that are typically inserted percutaneously into the venous or arterial vasculature, including flexible elongate bodies. Currently these goals are achieved using x-ray imaging and in some

cases ultrasound imaging. This invention provides a method to substantially increase the accuracy and reduce the need for imaging related to placing an intravascular catheter or other device. Reduced imaging needs also reduce the amount of radiation that patients are subjected to, reduce the time required for the procedure, and decrease the cost of the procedure by reducing the time needed in the radiology department.

The vasculature of mammals has long been accessed to provide therapy, administer pharmacological agents and meet other clinical needs. Numerous procedures exist in both venous and arterial systems and are selected based on patient need. One challenge common to all vascular-based therapies is health care provider access to the specific location or section of the vascular tree.

One common venous access procedure is central venous access. Central venous access is the placement of a venous catheter in a vein that leads directly to the heart. Central venous catheters are ubiquitous in modern hospital and ambulatory medicine, with up to 8 million insertions per year in the U.S. and a similar number outside the U.S.

Venous access devices are most often used for the following purposes:

- Administration of medications, such as antibiotics, chemotherapy drugs, and other IV drugs
- Administration of fluids and nutritional compounds (hyperalimentation)
- Transfusion of blood products
- Hemodialysis
- Multiple blood draws for diagnostic testing.

Central venous access devices are small, flexible tubes placed in large veins for people who require frequent access to their bloodstream. The devices typically remain in place for long periods: week, months, or even longer.

Central venous access devices are usually inserted in 1 of 3 ways:

- a) Directly via a catheter. Catheters are inserted by tunneling under the skin into either the subclavian vein (located beneath the collarbone) or into the internal jugular vein (located in the neck). The part of the catheter where medications are administered or blood drawn remains outside of the skin.
- b) Through a port. Unlike catheters, which exit from the skin, ports are placed completely below the skin. With a port, a raised disk about the size of a quarter or half dollar is felt underneath the skin. Blood is drawn or medication delivered by placing a tiny needle through the overlying skin into the port or reservoir.
- c) Indirectly via a peripheral vein. Peripherally inserted central catheter (PICC) lines, unlike central catheters and ports, are not inserted directly into the central vein. A PICC line is inserted into a large vein in the arm and advanced forward into the larger subclavian vein.

Central catheters and ports are usually inserted by a surgeon or surgical assistant in a surgical suite. An alternative is placement under the guidance of a special x-ray machine so that the person inserting the line can make sure that the line is placed properly. A PICC line can be put in at bedside, usually by a specially trained nurse. In this later case, confirmation by X-ray is currently required for assessing the success of the PICC placement.

Traditional surgically placed central catheters are increasingly being replaced by peripherally inserted central venous access devices. PICC lines usually cause fewer severe complications than central venous access devices. Peripherally Inserted-Central-Catheter (PICC) is used in a variety of clinical procedures. The PICC line placement procedure is

performed by interventional radiologists to deliver long-term drug delivery, chemotherapy procedures, delivery of intravenous medications or intravenous nutrition (hyperalimentation) and taking blood samples via a Hickman catheter. Insertion of PICC lines is a routine procedure in that it is carried out fairly often for a variety of treatments, and more than once in the same patient when the catheter is to be left in place for any length of time. Even though it is routine, it is a very time and labor-intensive procedure for the hospital staff, which also makes it expensive. During the procedure the physician or nurse places the catheter into a superficial arm vein such as the cephalic, basilic, antecubital, median cubital, or other superficial vein with the goal of having the distal end of the catheter reach the superior vena cava. After entering the superficial vein around the area where the arm bends (elbow), the catheter is advanced up the subclavian vein, then the brachiocephalic vein and finally it enters the superior vena cava. One caveat is to make sure that the PICC line does not enter the jugular vein via the subclavian vein.

Pulmonary artery catheterization is another example of a procedure utilizing venous access procedures. Pulmonary Artery Catheters (PAC), also known as Swan-Ganz or right heart catheters, provide information regarding the central venous, right heart, and pulmonary arterial blood pressures, thermodilution measurements that are useful for calculating cardiac output and related physiological parameters, access for drug delivery, and blood sampling at various intervals along the length of the catheter. PACs can lead to several complications in a patient. These complications include arrhythmias, rupture of the pulmonary artery, thrombosis, infection, pneumothorax, bleeding, etc. Complications can arise due to improper insertion, use, and/or maintenance of the catheter in the patient.

Hemodialysis therapy via a hemodialysis catheter is another example of a procedure requiring central venous access. A dialysis catheter is a specialized type of central venous catheter used for dialysis. Dialysis catheter placement involves the insertion of a catheter into a large vessel, utilizing X-ray guidance. The challenges of inserting a hemodialysis catheter in terms of guidance and positioning are similar to those of a central venous catheter, only they are typically larger and require a peel-away sheath for insertion.

Another therapy achieved via providing access to the venous system is the percutaneous treatment of varicose veins. Published population studies indicate that approximately 25 million people in the U.S. and 40 million people in Western Europe suffer from symptomatic venous reflux disease. Percutaneous treatment of varicose veins involves the placement of an energy delivery catheter (laser or RF) after navigation the vasculature to locate the treatment site. One common treatment site is the sapheno-femoral junction and less common sites are the sapheno-popliteal junction and sites of perforator veins, which connect the superficial venous system to the deep venous system of the leg at a variety of different locations, mostly below the knee. As such, in the case of percutaneous treatment of varicose veins using specific venous junctions, the position the laser or the RF catheter at an optimal location with respect to the venous junction is critical for the success of the intervention.

In addition to guiding the catheter through the vasculature, the location of the catheter tip is very important to the success of the procedure. Catheters will generally function equally well for pressure measurement and fluid infusion if the tip is situated in any major vein, above or below the heart. For dialysis or the infusion of irritant/hypertonic fluids, a high rate of blood flow past the catheter tip is desirable and this requires the placement of the luminal opening in as large a

vessel as possible. However, the package inserts of many central venous catheters give very strong warnings about the absolute requirement for catheter tips to lie outside the heart to avoid perforation and subsequent pericardial tamponade. Likewise positioning the catheter tip away from small peripheral veins is important to avoid damaging the vein wall or occluding the vein due the caustic effects of the infusing solution. It is also of major interest that the catheter tip stays in place after placement for the whole duration of the treatment. If the catheter tip moves, not only its effectiveness diminished but, in some situations, it can perforate the heart. In the United States, the Food and Drug Administration has issued advice emphasizing this point. Typically, the interventional radiologist uses a fluoroscopic agent to delineate the veins in the body and subsequently verifies the correct positioning of the catheter tip using a post-operative X-ray. Currently, post-operative X-ray is performed routinely while some studies have shown that only 1.5% of the cases are subject to complications that would indeed require X-ray imaging.

Current methods for guiding PICC lines include external electromagnetic sensors and intravascular, e.g., ECG. In the case of electromagnetic sensors, the endovascular device is guided by assessing the distance between an electromagnetic element at the tip of the device, e.g., a coil and an external (out of body) receiver. This method is inaccurate because it does not actually indicate location in the vascular but distance to an outside reference. In the case of ECG-guided catheters, the classic increase in P-wave size, known as 'P-atriale', is a widely accepted criterion for determining location of central venous catheter tips in the proximity of the sino-atrial node. Current methods include using a catheter filled with saline and an ECG adaptor at the proximal end connected to an ECG system. This method is inaccurate because it does not indicate location in the blood vessel but the proximity of the sino-atrial node. Because of known inaccuracies, all the current methods in use do explicitly require the use of a confirmatory chest X-ray to verify and confirm location of the tip of the endovascular device at the desired target in the vasculature. Most prior art relating to the use of intravascular ultrasound or electrical mapping of heart activity for diagnostic and therapeutic purposes addresses problems independently: some addresses ultrasound guidance on the arterial side such as that described by Franzin in Doppler-guided retrograde catheterization using transducer equipped guide wire (U.S. Pat. No. 5,220,924) or that described by Katims in Method and apparatus for locating a catheter adjacent to a pacemaker node of the heart (U.S. Pat. No. 5,078,678). Such approaches have intrinsic limitations which does not make them suited to solve the problem addressed by the current invention. The limitations of the Franzin approach have been extensively explained in VasoNova patent applications US 20070016068, 20070016069, 20070016070, and 20070016072. Limitations of an approach based exclusively on measuring right-atrial electrocardiograms have been described in the literature, for example in [1]: W. Schummer et al., Central venous catheters—the inability of 'intra-atrial ECGG' to prove adequate positioning, *British Journal of Anaesthesia*, 93 (2): 193-8, 2004.

What is needed are methods and apparatuses to optimize guidance and placement of catheters in order to reduce the risk associated with wrong placement and the cost associated with the X-ray imaging. Further there remains a need for a catheter guidance and placement system that may be used to safely guide and place catheters in healthcare provider or clinical environments other than in the radiology department or surgical suite wherein a radiological or other external



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imaging modality is used to confirm catheter placement. As such, there remains a need in the medical arts for instruments, systems and associated methods for locating, guiding and placing catheters and other instruments into the vasculature generally. In addition remains a need in the medical arts for instruments, systems and associated methods for locating, guiding and placing catheters and other instruments into the vasculature to meet the challenges presented by the unique characteristics and attributes specific to the vascular system of interest. The current invention overcomes the above described limitations by making use of physiological parameters like blood flow and ECG measured in the vasculature and is based on the fact that physiological parameters and their relationship is unique to the locations in the vasculature where the endovascular devices needs to be placed. The current invention describes an apparatus for identifying the unique physiological signature of a certain location in the vasculature and a method to guide the endovascular device to that location based on the physiological signatures.

#### SUMMARY OF THE INVENTION

An aspect of the invention includes a method of evaluating flow characteristics in a vessel of a patient. In some embodiments, the method includes the steps of positioning a catheter having a balloon at a measuring location within the vessel; transmitting an ultrasound signal into the vessel while the balloon catheter is within the measuring location; evaluating a reflection of the ultrasound signal to determine a flow parameter within the vessel while the catheter is in the measuring position; expanding the balloon within the vessel at the measuring location; and stopping the expanding step when the result of the evaluating step is that the flow through the vessel is substantially stopped. In some embodiments, the measuring location is within a pulmonary artery, within a branch of the pulmonary artery, and/or is a pulmonary artery wedge position.

In some embodiments, the transmitting step further comprises transmitting an ultrasound signal into the vessel from an ultrasound transducer on the balloon catheter. In some embodiments, the transmitting step further comprises transmitting an ultrasound signal into the vessel during the expanding step. In some embodiments, the transmitting step further comprises transmitting a non-imaging ultrasound signal into the vessel. In some embodiments, the transmitting step further comprises transmitting an A-mode ultrasound signal into the vessel. While in some embodiments, the transmitting step further comprises transmitting Doppler ultrasound signal into the vessel.

In some embodiments, the evaluating step further comprises receiving a reflected ultrasound signal with an ultrasound transducer on the balloon catheter. In some embodiments, the evaluating step further comprises determining blood flow velocity and/or blood flow intensity within the vessel and the stopping step further comprises stopping the expanding step when the determined blood flow velocity and/or blood flow intensity indicates that the flow through the vessel has substantially stopped. In some embodiments, the evaluating step further comprises determining a blood flow signature pattern within the vessel and the stopping step further comprises stopping the expanding step when the determined blood flow signature pattern indicates that the flow through the vessel has substantially stopped. In some embodiments, the evaluating step further comprises determining a pressure signature pattern within the vessel and the stopping step further comprises stopping the expanding step when the determined pressure signature pattern indicates that the flow

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through the vessel has substantially stopped. In some embodiments, the stopping step further comprises stopping the expansion of the balloon when the ultrasound transducer receives a reflected ultrasound signal that indicates that the flow through the vessel has substantially stopped. In some embodiments, the stopping step further comprises stopping the expanding step when the result of the evaluating step is that the pressure at the measuring location within the vessel has dropped below the mean pulmonary arterial pressure. In some embodiments, the stopping step further comprises stopping the expanding step when the result of the evaluating step is that the pressure signature pattern at the measuring location within the vessel is consistent with a pulmonary capillary wedge pressure signature pattern. In some embodiments, the pressure signature pattern indicates a pressure lower than a pulmonary artery pressure and a pressure more static than a pulmonary artery pressure. In some embodiments, the stopping further comprises stopping the expanding step when the balloon expanding pressure is at least equal to a systolic pulmonary arterial pressure.

In some embodiments, the method further comprises the step of deflating the balloon. In some embodiments, the evaluating step further comprises evaluating a reflection of the ultrasound signal to determine a flow parameter within the vessel after the balloon is deflated. In some embodiments, the evaluating step further comprises determining a blood flow signature pattern within the vessel. In some embodiments, wherein the blood flow signature pattern indicates turbulent blood flow as the balloon deflates and decouples from the vessel wall. In some embodiments, the method further comprises the step of verifying that flow parameter within the vessel determined after the balloon is deflated is substantially similar to the flow parameter within the vessel determined before the balloon is inflated.

In some embodiments, the method further comprises the step of detecting an endovascular electrogram signal with a sensor on the endovascular device. In some embodiments, the endovascular electrogram comprises electrical activity from the heart, while in some embodiments the electrical activity of the heart is related to the sino-atrial node of the heart. In some embodiments, the timing of the expanding step is based on the electrogram signal. In some embodiments, the result of the evaluating step is a combined evaluation of the ultrasound signal and the electrogram signal. In some embodiments, the method further comprises the step of measuring a parameter used to determine cardiac function. In some embodiments, the measuring step further comprises measuring pulmonary artery occlusion pressure. In some embodiments, the timing of the measuring step is based on the electrogram signal, and in some embodiments, the measuring step further comprises measuring arterial flow.

In some embodiments, the positioned step further comprises the steps of advancing the balloon catheter into the vessel; transmitting an ultrasound signal into the vessel using an ultrasound transducer on the balloon catheter; receiving a reflected ultrasound signal with the ultrasound transducer; and positioning the endovascular device based on the ultrasound signal. In some embodiments, the method further comprises the step of processing the reflected ultrasound signal received by the ultrasound transducer. In some embodiments, the result of the processing step includes information related to blood flow direction. In some embodiments, the flow direction comprises a flow directed towards the sensor and a flow directed away from the sensor. In some embodiments, the result of the processing step includes information related to blood flow velocity and/or blood flow intensity. In some

embodiments, the result of the processing step includes information related to ultrasound A-mode information.

Another aspect of the invention includes a method of evaluating flow characteristics in a vessel of a patient. In some embodiments, the method includes the steps of positioning a catheter having a balloon at a measuring location within the vessel; transmitting a first ultrasound signal into the vessel while the balloon catheter is within the measuring location; evaluating a reflection of the first ultrasound signal to determine a first flow parameter of the vessel while the balloon is in a first configuration; expanding the balloon within the vessel at the measuring location; transmitting a second ultrasound signal into the vessel during the expanding step; evaluating a reflection of the second ultrasound signal to determine when the blood flow through the vessel is substantially stopped; returning the balloon to the first configuration; transmitting a third ultrasound signal into the vessel after the returning step; and evaluating a reflection of the third ultrasound signal to determine a third blood flow parameter of the vessel. In some embodiments, the first configuration of the balloon is a stowed configuration, while in some embodiments the first configuration of the balloon is a partially inflated configuration. In some embodiments, the method further comprises the step of verifying that first flow parameter of the vessel is substantially similar to the third flow parameter of the vessel.

Another aspect of the invention includes a method of evaluating flow characteristics in a vessel of a patient. In some embodiments, the method includes the steps of positioning a catheter having a balloon at a measuring location within the vessel; transmitting an ultrasound signal into the vessel while the balloon catheter is within the measuring location; detecting an electrogram signal while the balloon catheter is within the measuring location; evaluating a reflection of the ultrasound signal and the electrogram signal while the catheter is in the measuring position; expanding the balloon within the vessel at the measuring location; stopping the expanding step when the result of the evaluating step is that the flow through the vessel is substantially stopped; and measuring a parameter used to determine cardiac function, wherein the timing of the measuring step is based on the result of the evaluation step. In some embodiments, the result of the evaluating step is a combined evaluation of the ultrasound signal and the electrogram signal.

Another aspect of the invention includes a balloon catheter system. In some embodiments, the balloon catheter system includes a catheter adapted and configured to be inserted into a patient's vasculature, an expandable balloon coupled to the catheter towards the distal end of the catheter, and an ultrasound sensor coupled to the catheter distal to the balloon. In some embodiments, the balloon catheter is a Swan-Ganz catheter. In some embodiments, the catheter may be at least 55 to 75 cm in length, and may include incremental markings to gauge insertion length. In some embodiments, the catheter includes multiple lumens. In some embodiments, the balloon is expandable. In some embodiments, the balloon has a first configuration. In some embodiments, the first configuration may be a fully stowed configuration, or in some embodiments, the first configuration is a partially inflated position. In some embodiments, the balloon catheter system may further include an ECG sensor coupled to the catheter distal to the balloon. In some embodiments, the balloon catheter may include more than one ECG sensor. In some embodiments, the ECG sensors are spaced along the catheter at various intervals.

#### INCORPORATION BY REFERENCE

All patents, publications and patent applications mentioned in this specification are herein incorporated by refer-

ence in their entirety to the same extent as if each individual patent, publication or patent application was specifically and individually indicated to be incorporated by reference.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The novel features of the invention are set forth with particularity in the appended claims. A better understanding of the features and advantages of the present invention will be obtained by reference to the following detailed description that sets forth illustrative embodiments, in which the principles of the invention are utilized, and the accompanying drawings of which:

FIG. 1 illustrates an overview of the endovascular device guiding apparatus and method disclosed in the present invention.

FIG. 2 illustrates an endovascular device with multiple sensors.

FIG. 3A-3B illustrates an intravascular ECG electrode which can be used for steering and moving the endovascular member away from the vessel wall.

FIG. 4A-4C illustrates the concept of removable sensor core, whereby a stylet with integrated sensors can be inserted into and removed from an endovascular device like a catheter at any time.

FIG. 5A-5B illustrates an embodiment integrated sensors in an endovascular device with braided shaft and atraumatic tip.

FIG. 6 illustrates another embodiment of integrated sensors in an endovascular device with stylet-like reinforcement that can be used as an ECG electrode.

FIG. 7 illustrates the flow velocity profiles, the intravascular ECG signal and their correlation as detected by the device according to the present invention in the superior vena cava as documented by the synchronized fluoroscopic image.

FIG. 8 illustrates the flow velocity profiles, the intravascular ECG signal and their correlation as detected by the device according to the present invention at the caval-atrial junction as documented by the synchronized fluoroscopic image.

FIG. 9 illustrates the flow velocity profiles, the intravascular ECG signal and their correlation as detected by the device according to the present invention in the internal jugular vein as documented by the synchronized fluoroscopic image.

FIG. 10 illustrates the use of intravascular ECG signal to gate or trigger the acquisition or processing of the blood flow information.

FIG. 11 illustrates the effect of using additional gating based on patient's breathing on the acquisition and processing of blood flow information.

FIG. 12 illustrates the use of intravascular ECG signals in case of a-fib patients.

FIG. 13 illustrates a graphical user interface displaying blood flow information, intravascular ECG signals, their correlation, and catheter tip location information based on the above. FIG. 13 also illustrates the use of A-mode imaging for clot identification inside the blood stream or inside an endovascular member.

FIG. 14A-14D illustrates a simplified user interface using blood flow information, intravascular ECG signals and their correlation to display if the endovascular member is advancing towards the caval-atrial junction and sinoatrial node, if the endovascular member is advancing away from the caval-atrial junction and sinoatrial node, or if the endovascular member is at the caval-atrial junction proximal to sinoatrial node.

FIG. 15 is a flow chart of an exemplary endovascular placement method.

FIG. 16 illustrates an endovascular device within the vasculature at various locations according to the method of FIG. 15.

FIGS. 17 and 18 are various views of the heart and surrounding vasculature.

FIG. 19 is a flow chart illustrating the functioning of a data acquisition system of FIG. 6.

FIG. 20 is a flow chart illustrating an exemplary software block diagram of FIG. 6.

FIG. 21 is a flow chart illustrating an exemplary processing algorithm for multi-parameter signal processing and correlation.

FIGS. 22A and 22B illustrate an embodiment of a balloon catheter including an ultrasound sensor and an ECG sensor.

FIGS. 23-27 are a flow charts illustrating methods for evaluating flow characteristics in a vessel.

## DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the present invention provide guided vascular access devices, systems for processing signals from the guided vascular access devices and user interface for providing information to a user based on outputs from the processing system. FIG. 1 illustrates one embodiment of an exemplary endovascular access and guidance system 100. The system 100 includes an elongate body 105 with a proximal end 110 and a distal end 115. The elongate body 105 is any of a variety of endovascular devices adapted to insertion into and navigation through the vasculature of the patient 1. FIG. 1 illustrates the distal end 115 inserted into the basilic vein 6. The expected path of travel (dashed line 20) in this illustrative example is into the a portion of the heart 20 or within the superior vena cava 14 in proximity to the sinoatrial node (SA node) 8. The aorta 3, the pulmonary arteries, pulmonary veins 11, the jugular veins 10, the brachiocephalic vein 12, inferior vena cava 16 and atrioventricular node (AV node) 9 are also represented in this view.

Not shown in FIG. 1 but further described below, the elongate body 105 includes at least two sensors for measuring physiological parameters in the body. In some embodiments, one sensor is a non-imaging ultrasound transducer on the elongate body 105 configured to provide in vivo non-image based ultrasound information of the vasculature of the patient 1. In some embodiments, the other sensor is an endovascular electrogram lead on the elongate body 105 in a position that, when the elongate body 105 is in the vasculature, the endovascular electrogram lead electrical sensing segment provides an in vivo electrogram signal of the patient 1. FIG. 1 illustrates the use of a second electrogram sensor that is outside of the vasculature. The electrode 112 is positioned external to the vasculature of the patient 1. The electrode 112 detects electrogram information that is transmitted via lead 111 to the processor 140.

Alternatively, in place of the electrode 112 or in addition to the electrode 112 another electrogram sensor may be placed on the elongate body 105. More than one electrogram sensor may be provided on the elongate body. In this case, the processor 140 would also be configured to receive, process, compare and correlate the electrogram information from the additional electrogram sensor (or other sensors) provided by the elongate body 105. The electrogram leads or sensors on the elongate body 105 may also be placed relative to the elongate body 105 and to one another in order to obtain a target electrogram signal and a baseline electrogram signal in order to facilitate the position and location capabilities of the guidance system 100. The target and baseline electrogram information may be related to one or more of: (a) electrical

activity of the heart including all or a portion of an electrocardiogram (ECG); (b) electrical activity of the brain including all or part of an electroencephalogram (EEG); and (c) electrical activity of a muscle or muscle group including all or part of an electromyogram (EMG) related to that muscle or muscle group. Additional details of the sensors and the various alternative configurations of the elongate body 105 are described below in at least FIGS. 2-5B.

The system 100 also includes a processor 140 configured to receive and process a signal from the non-imaging ultrasound transducer and a signal from the endovascular electrogram lead. The processor 140 includes conventional processing capabilities to receive and process ultrasound and electrogram signals as with conventional ultrasound and electrogram signals. The conventional processing capabilities include those conventional components needed to receive process and store the corresponding sensor data. If sensors on the elongate body are used to detect ECG activity, then appropriate electrocardiography components and processing capabilities is provided. The same is true for EEG signal processing, EMG signal processing, acoustic sensor processing, pressure sensor processing, optical sensor processing and the like.

However, unlike conventional ultrasound and electrogram systems, processor 140 includes programming and processing capabilities to process the signals from the sensors to identify and correlate flow and electrical patterns to aid in the guidance, positioning and confirmation of location of the elongate body 105 as described herein.

In one aspect, the processor 140 is adapted and configured using software, firmware or other programming capabilities to receive and process a signal from the non-imaging ultrasound transducer that contains at least one signal of the group consisting of: a venous blood flow direction, a venous blood flow velocity, a venous blood flow signature pattern, a pressure signature pattern, A-mode information and a preferential non-random direction of flow. Additionally, the processor 140 is further adapted and configured using software, firmware or other programming capabilities to receive and process a signal from the endovascular electrogram lead that contains at least one signal from the group consisting of: an electrocardiogram signal, a P-wave pattern, a QRS-complex pattern, a T-wave pattern, an EEG signal and an EMG signal.

In one aspect, the signal from one sensor is the trigger for acquisition or processing of a signal from another sensor. In this manner, the data from two different physiologic sensors may be correlated in time and to the trigger signal. Alternatively, rather than triggering acquisition data from the triggered sensor, all sensor data could be collected and/or stored and the trigger could instead result in the processing of only the subset of the data based on the trigger data. In either triggering scheme, the trigger sensor data and the triggered sensor data are processed together to yield the benefits described below. One example of triggering is the use of the P-wave detection from an electrogram sensor as the triggering signal for acquiring ultrasound data from an ultrasound sensor. As described below, the unique P-wave signal detected when an electrogram lead is positioned in the superior vena cava near the sino-atrial node 8 can be used to confirm the detection of the unique blood flow pattern that also occurs in this area of the vasculature. In this way, the existence of both unique physiological signals from two different physiological systems increases the accuracy of the guidance system embodiments described herein.

The system 100 also includes an output device 130 configured to display a result of information processed by the processor 140. The display device may, like the processor 140,

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include capabilities found in conventional display devices. The display device 140 of the invention differs from the conventional display in that the display is configured to display information related to the unique processing and results determined by processor 140. In one aspect, the output device 140 displays a result related to a position of the elongate body within the vasculature of the patient. In another aspect, a result of information processed by the processor includes an indication of a position or a movement of the elongate body 105 within the vasculature based on in vivo non-image based ultrasound information and in vivo electrogram information. The display 130 would be configured to display this information for a user to perceive in any suitable manner such as visually, with colors, with pictograms, with sounds or in other appropriate manners.

Other aspects of embodiments the invention relate to the use of intravascularly measured physiological parameters for locating, guiding, and placing catheters in the vasculature. In one aspect, embodiments of the present invention relate to an endovascular member assembly with built-in sensors for measuring of physiological parameters such as blood flow, velocity, pressure, or intravascular ECG. In a different aspect, embodiments of the invention relate to data processing algorithms that can identify and recognize different locations in the vasculature based on the pattern of physiological parameters measured at that location. In still another different aspect, embodiments of the present invention relate to data processing algorithms that can identify and recognize structures such as objects of interest in the vasculature or in endovascular members, e.g., blood clots based on the pattern of parameters measured, e.g., A-mode and blood flow velocity. In an additional aspect, embodiments of the present invention relate to an instrument that has a user interface which shows guiding and positioning information and presents the objects of interest, e.g., blood clots. For example, in this aspect the processor is further configured to process a signal from the non-image ultrasound transducer and to indicate in the output device information related to the presence of a structure in the field of view of the non-imaging ultrasound transducer.

In still another aspect, embodiments of the invention relate to the method of guiding and positioning an endovascular member within the vasculature by the user based on location information provided by the sensor-based endovascular member. Other various aspects of embodiments the invention relate to the use of intravascularly measured physiological parameters for locating, guiding, and placing catheters or stylets or guide wires for use as guides to particular locations within the vasculature that have been identified using the guided vascular access devices and systems described herein.

The present invention provides a new methods, devices and systems for intravascular guidance and placement of endovascular devices based on the recognition of patterns in the signals for different physiological parameters and correlation of those signal patterns. In one exemplary application, a catheter, such as a peripherally inserted central catheter (PICC) is inserted, advanced, positioned and monitoring within the vasculature based on the recognition of blood flow patterns, of the electrocardiogram signals and of their correlation at the locations of interest.

One benefit of the new apparatus and method introduced herein is that it increases the probability of correct placement of an endovascular device in a placement procedure performed at the bedside. Moreover, because of the accuracy and redundancy of the positioning methods described herein, it is believed that the use of the inventive methods, devices and systems will allow for endovascular device placement without the need for imaging guidance, in particular without

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X-ray imaging and/or imaging for confirmation of placement and lack of device migration. Another benefit of the new apparatus and method introduced herein is that it allows the detection of blood clots in the vasculature or in catheters such as identifying the cause for a malfunctioning catheter, e.g., a central line.

Yet another benefit is related to the fact that the guided vascular access devices and the systems described herein may be inserted into the existing healthcare workflow for placing endovascular devices into the vasculature. More specifically, embodiments of the invention provide new sensor based endovascular devices, systems and methods for intravascular guidance and placement of, for example, sensor based catheters and/or guide wires. Then, the properly positioned sensor based endovascular device is used to then guide the deployment of other endovascular devices or facilitate the performance of other diagnostic or therapeutic procedures in the body such as, for example: (a) location of heart valves for replacement heart valve procedures; (b) identification of the renal veins for therapy in those veins or in the kidneys; (c) identification of renal veins and/or the inferior vena cava for IVC filter placement; (d) location of coronary sinus for placement of pacing leads or mitral valve modification devices; and (e) location of pulmonary veins for sensor placement and/or performance of therapy such as ablation treatment for atrial fibrillation; as well as a wide variety of other diagnostic or therapeutic procedures that would benefit from the placement of device or performance of therapy at specific locations in the vasculature identified by the sensor correlation techniques described herein.

In some embodiments, the systems and methods of embodiments of the inventive guidance system described herein are utilized to locate, guide and position catheters and/or guide wires equipped with sensors described herein within the vessels of the venous system. The embodiments described herein may also be utilized in the vessels of the arterial system as well. In one aspect, the guided vascular access devices described herein may be used for the guidance, positioning, and placement confirmation of intravascular catheters used in a wide number of clinical applications. Exemplary clinical applications that would benefit from embodiments of the invention include the placement of, for example, central venous access catheters (PICC), hemodialysis catheters and the placement of catheters, positioning of endovascular devices in the vasculature of the brain for treatment of stroke, placement of leads or other brain based therapy or therapy devices or treatment systems for percutaneous treatment of varicose veins. Moreover, particular muscles or muscle groups may be selected for EMG stimulation and/or sensor collection in support of one of more methods and devices described herein where the EMG signals are used to confirm and/or correlate a position in the vasculature. This aspect may be particularly helpful when identifying portions of the vasculature in the legs for localization of varicose veins, localization of the femoral veins or positioning of a vessel harvesting device within the great saphenous vein, for example.

While desiring not to be bound by theory, it is believed that certain locations in the vasculature can be identified by specific blood flow and electrogram patterns, electrogram signal patterns and correlation between these blood flow patterns at those locations. These patterns may be based on, for example, blood pressure, Doppler blood flow measurements, and intravascular electrocardiogram. Moreover, it is believed that the direction of travel for an sensor equipped endovascular device can be determined relative to the direction of blood flow by using the Doppler effect, relative changes in the intravascular

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electrogram signal and in the correlation between the blood flow and electrogram information.

For example, in the case of a Peripheral Inserted Central Catheter (PICC) line, by determining and real-time monitoring the direction of the catheter movement in the blood vessels using the sensors, techniques, data acquisition and processing described herein (for example blood flow and electrogram information), a user receives feedback on advancing a guided vascular access device to allow the PICC to advance along a desired path from an insertion vein into the vena cava and towards the sinoatrial node. The system may also recognize unintended entry into other veins because of the differences in flow patterns signals and electrogram signals or other signals received from the sensors. As such, the system may recognize unintended entry into the right atrium, inferior vena cava, jugular vein, the subclavian vein. Additionally, the system may detect when a sensor is against the vessel wall. By monitoring the data acquired from sensors positioned on the endovascular access device, the user can be notified when the device tip reaches the ideal placement in the lower third of the superior vena cava, at the caval-atrial junction and/or in the proximity of the sinoatrial node. The system recognizes these locations of the vena cava, and other vascular components, by analyzing sensor acquired data to identify unique flow patterns and electrogram signatures and to correlate these unique signatures in order to confirm placement, location and/or guidance.

The ultrasound technology described herein is a non-imaging ultrasound used in combination with intravascular electrograms, or other physiological parameter sensor data. The unique flow patterns may be discerned using non-imaging ultrasound and as such does not require all the elements that make ultrasound imaging possible, such as scanning with a moving transducer or working with phased arrays and beam forming, and the like. As such, embodiments of the present invention provide a vascular access and guidance system with a hand-held, simple, inexpensive user interface. Non-imaging ultrasound includes a number of various ultrasound techniques and processing configurations, by way of non-limiting example: A-beam ultrasound, Doppler ultrasound, continuous wave Doppler ultrasound, pulsed Doppler ultrasound, color Doppler ultrasound, power Doppler ultrasound, bi-directional Doppler ultrasound, and ultrasound techniques that provide for the determination of velocity profile based on correlation of blood flow and time.

One benefit of the methods, devices and systems described herein is the use of a "multi-vector" or "multi-parameter" approach. The multi-vector approach refers to the use of the blood flow information, the electrical activity information and the relationship between the two. The physiological information is analyzed in order to identify the location in the vasculature where the information was acquired. Because body functions are unique at certain corresponding unique locations in the vasculature, embodiments of the present invention can use measurements of the body functions and detect location in the body.

In particular, the present invention describes the use of the blood flow profile and of the intravascular ECG to detect the proximity of the sinoatrial node and of the caval-atrial junction. FIG. 17 illustrates the anatomical location of the caval-atrial junction at the confluence between the superior vena cava (SVC) and inferior vena cava (IVC) just before entering the right atrium (RA). FIG. 18 illustrates the anatomical location of the sinoatrial node at the caval-atrial junction. The function of the vasculature and the function of the heart are unique at the caval-atrial junction both in terms of blood flow profile and of electrical activity of the heart.

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For example, the system according to the present invention identifies the blood flow profile characteristic of the caval-atrial junction and ECG waveform patterns characteristic of the proximity of the sinoatrial node and, when both these patterns are present, indicates to the user that the desired target location has been reached. One benefit of this approach is that the blood flow and the electrical activity are independent physiological parameters and thus by considering them together, the accuracy of the location information is significantly improved. In addition the intravascular electrogram signal can be used for selective (gated) acquisition and processing of the blood flow information, depending upon the specific characteristics of the electrogram signal being utilized. For example when the electrogram signal is produced by the heart from the gating acquisition may be based on one or more integrals of the heart cycle. This selective approach also increases the accuracy of determining blood flow patterns corresponding to locations in the vasculature.

#### Endovascular Member with Sensors for Guidance

FIG. 2 illustrates an endovascular device 150 having an elongate body 105 with a proximal end 110 and a distal end 115. There is a non-imaging ultrasound transducer 120 on the elongate body 105. There is an atraumatic tip 121 on the endovascular device 150. The atraumatic tip 121 may also include an ultrasound lens. The ultrasound lens may be used to shape the ultrasound signal produced by the ultrasound transducer 120. In one aspect the ultrasound lens is a divergent lens.

The endovascular device 150 also has an opening 182 in the elongate body 105 and a lumen within the elongate body 105 in communication with the opening 182 and the elongate body proximal end 110. As illustrated, there may be one or more openings 182 in communication with one or more lumens or tubes 183. Also shown on the proximal end 110 are the various connections to the sensors and lumens in the endovascular device 150. These connections are conventional and may take any suitable form to connect the endovascular device to the other guidance system 100 components such as the processor, display or fluid delivery device. As such, by using additional lumens or other access features, the elongate body 105 or endovascular device 150 is adapted to deliver a therapy to the patient such as by delivering drugs, therapeutic or diagnostic agents through the openings 182 or between the inner and outer tubes. In yet another alternative configuration, the elongate body 105 or the endovascular device 150 is adapted to provide endovascular access for another device.

The endovascular device 150 also illustrates how other additional and optional sensors may be provided. Embodiments of the endovascular device 150 may contain any of a number of different sensors. The sensor is selected based on the physiological parameter to be measured and used in the guidance, positioning and correlation methods described herein. By way of non-limiting example, the device may include an ultrasound sensor, a conductive wire, a pressure sensor, a temperature sensor, a sensor for detecting or measuring electrical potential and voltages and other sensors suited to collecting physiological information and providing information to the processor 140 for processing in an algorithm or for other suitable form of analysis based on the techniques described herein. The sensor-based endovascular device 150 can be used independently to deliver a payload into the vasculature, e.g., a drug or to draw blood or it can be inserted into the one of the lumens of another endovascular device, e.g., a catheter. Then the entire assembly can be

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inserted into the patient's body, e.g., for a PICC placement procedure, or through a catheter **90** (see FIG. **4C**).

Additionally or alternatively, the endovascular device **150** can be configured as any type of catheter, stylet, guidewire, an introducer, a combination thereof or any other type of device which allows for vascular access. The endovascular device and the corresponding connection from the sensors to the proximal end can either be fixed in the endovascular device, or pre-inserted and removable after procedure, or reinsertable for location verification post placement. In one embodiment the endovascular device integrates a single lead electrode for electrical activity monitoring. In a different embodiment, the endovascular device may integrate several electrodes (leads), for example one at the very distal tip of the endovascular member and one more proximal such that the distal electrode can detect the electrical activity of the heart while the more proximal electrode can serve as a reference for measuring since the more proximal electrode is closer to the patient's skin and further away from the heart. In addition to providing electrical mapping, the lead/electrode can be used as a steering element to steer and position the endovascular device as illustrated in FIGS. **3A**, **3B**, **4A** and **4B**.

According to the embodiments of the present invention physiological information is acquired by sensors and transmitted to a processor. The processor uses algorithms which analyze and process the sensor data to provide information on the location of the sensor core assembly and of the corresponding endovascular device in the patient's vasculature. Since high degree of accuracy is desired, different types of physiological information, ideally independent from each other, such as blood flow information and electrogram information are used to accurately characterize the direction of movement and location. In one aspect of the present invention, the described clinical need is met by gathering physiological information regarding blood flow using ultrasound and regarding the electrical activity of the heart by acquiring endovascular electrical signals.

By way of example, the endovascular device embodiments of FIGS. **3A**, **3B**, **5A**, **5B**, consists of an elongate body **105** that may be configured as any of a catheter, a stylet, or a guidewire that is configured for endovascular access. Moreover, the catheter, stylet or guidewire may be of the one part or two part construction described herein.

The endovascular device **150** may be configured as a single structure (FIGS. **3A**, **3B**, **4A**, **4B**, **5A** and **5B**, also be a removable device or sensor core assembly may consist of a non-imaging ultrasound transducer mounted at the end of a piece of tubing. The tubing can be single or multi-lumen and can be made of any of a variety of polymeric, or elastomeric materials. The lumens may be used to support the sensors on the tubing or may be used for delivery of therapeutic or diagnostic agents. One or more physiological parameter monitoring sensors may be positioned on the tubing as described herein. The endovascular device may have a two part construction as shown in the illustrative embodiment of FIG. **2** where the ultrasound transducer is on a tube (an inner tube) within another tube (an outer tube).

In the illustrative embodiment of FIG. **2**, the inner tube carries the ultrasound transducer. The outer tube, possibly a multi-lumen tube, has a lumen for the inner tube. Additionally, lumens **183** are provided to correspond to the openings **182**. The outer tube also supports the additional sensors (one sensor **186** is shown). The wiring or other connections for the additional sensors **186** or electrogram lead may also be provided with their own lumen or lumens. The proximal end **110** and the various leads and lumens and other connections may

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be placed into a single connector used to attach the endovascular device **150** to the other components of the system **100**.

Whether the endovascular device **150** is a single tube or a multiple tube construction, the device include an additional sensor **186** on the endovascular device for measuring a physiological parameter. In one aspect, the additional sensor is an optical sensor and the physiological parameter is related to an optical property detected within the vasculature. In another aspect, the additional sensor is a pressure sensor and the physiological parameter is related to a pressure measurement obtained within the vasculature. In another aspect, the additional sensor is an acoustic sensor and the physiological parameter is related to an acoustic signal detected within the vasculature.

There is an endovascular electrogram lead **130** on the elongate body **105** in a position that, when the endovascular device **150** is in the vasculature, the endovascular electrogram lead **130** is in contact with blood. There are two endovascular leads **130** in the illustrated embodiment of FIG. **2**. As shown, there is an endovascular electrogram lead **130** positioned at the elongate body distal end **115**.

As used herein, an electrogram lead **130** contains at least one electrical sensing segment **135**. The electrical sensing segment **135** is that portion of the electrogram lead **130** that is used for detecting or sensing the electrical activity being measured. The electrical sensing segment **135** could be a portion of the lead **130** that is not insulated, it could be a separate structure, like an electrode, that is joined to the lead **130** or it could be a structure within the endovascular device (see FIG. **5B**). In one aspect, the electrical sensing segment of an endovascular electrogram lead is positioned within 3 cm of the elongate body distal end **115**. In another aspect, the electrical sensing segment **135** of an endovascular electrogram lead **130** is positioned within 3 cm of the non-imaging ultrasound transducer **120**. As shown in FIG. **2**, this aspect relates to the lead **130** that extends from the distal end or to the spacing of proximally positioned endovascular lead **130**. Additionally or alternatively, the electrical sensing segment **135** of an endovascular electrogram lead **130** is positioned proximal to the non-imaging ultrasound transducer **120**.

FIG. **2** also illustrates an endovascular device with a second endovascular electrogram lead **135** on the elongate body **105**. The second endovascular lead is shown in a position that, when the endovascular device **150** is in the vasculature, the second endovascular electrogram lead **130** is in contact with blood. Endovascular leads **130** (and/or the corresponding electrical sensing segment or segments **135**) may extend from the elongate body **105** as shown in FIGS. **2** and **3A** or may be integral to or within the elongate body as shown in FIGS. **3B**, **4A**, **4B**, **5A**, and **5B**. In one embodiment, the electrical sensing segment **135** of the second endovascular electrogram lead **130** (the proximal electrogram lead **130** in FIGS. **2** and **4B**) is positioned about 5 cm from the other endovascular electrogram lead **130**. Alternatively, electrical sensing segment **135** of the second endovascular electrogram lead **130** is positioned about 5 cm from the elongate body distal end **115**.

The use of two electrogram leads can be used to enhance the measurement accuracy of the electrical signals being used in the guidance system. In this regard, the electrical sensing segment of the second endovascular electrogram lead is positioned at a distance spaced apart from the endovascular electrogram lead so that the second endovascular electrogram lead detects a baseline electrogram signal when the endovascular electrogram lead is detecting a target electrogram signal. In this way, the system may rely completely on electrical signals completely within the vasculature to obtain a baseline measurement thereby eliminating the need for an external

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sensor as shown in FIG. 1. In this regard, the electrical sensing segment of the second endovascular electrogram lead is positioned such that when the electrical sensing segment of the endovascular electrogram lead is positioned to detect a targeted electrogram signal from the heart the electrical sensing segment of the second endovascular electrogram lead is positioned to detect a comparison baseline ECG signal. Alternatively, the electrical sensing segment of the second endovascular electrogram lead is positioned such that when the electrical sensing segment of the endovascular electrogram lead is positioned to detect a targeted electrogram signal from the brain the electrical sensing segment of the second endovascular electrogram lead is positioned to detect a comparison baseline EEG signal. In another alternative, electrical sensing segment of the second endovascular electrogram lead is positioned such that when the electrical sensing segment of the endovascular electrogram lead is positioned to detect a targeted electrogram signal from a muscle the electrical sensing segment of the second endovascular electrogram lead is positioned to detect a comparison baseline EMG signal.

There are also embodiments where the spacing between the electrogram leads is related to the target anatomy or anatomical structures. In one example, the electrical sensing segment of the second endovascular electrogram lead is positioned at a distance related to the length of the superior vena cava such that when the endovascular electrogram lead is in the superior vena cava the second endovascular electrogram lead is outside of the superior vena cava. Similarly, following the EEG and EMG examples above, one lead would be near a target region of the brain or a muscle and the second would be positioned so that it would detect baseline electrical levels.

The conductive element for an electrogram lead can be made up of any suitable biocompatible conductive material such as stainless steel, a saline column or SMAs (smart memory alloys or shape memory alloys), e.g., nitinol. The endovascular devices and sensors described herein are suited and configured for use in the vasculature and are thus sized and have appropriate finishes or coatings to facilitate endovascular use. Typical diameters of the conductive element are between 0.005" and 0.010". Typical lengths of the conductive element or the endovascular device are between 1 and 8 feet.

Moreover, in some aspects, the conductive element is sized and configured to perform multiple functions or functions in addition to signal detection and transmission. For example, the conductive element or electrogram lead may be used for steering, tip positioning, and others. FIGS. 3A and 3B illustrate an embodiment of an endovascular device 150 with an elongate body with a proximal end and a distal end. There is a non-imaging ultrasound transducer on the elongate body. There is an endovascular electrogram lead on the elongate body in a position that, when the endovascular device is in the vasculature, the endovascular electrogram lead is in contact with blood. The electrical sensing segment 135 is positioned to detect an electrogram signal. The electrical sensing segment 135 is positioned in the window 170 and can access blood. The window 170 is an opening into a lumen within the elongate body that forms a sliding seal about the electrogram lead 130. In this way, blood in contact with the window and the lead is prevented from flowing down the interior of the elongate body.

As best seen in FIGS. 3A and 3B, the endovascular electrogram lead 130 is moveable from a stowed condition within the elongate body (FIG. 3B) and a deployed condition outside of the elongate body (FIG. 3A). As best seen in FIG. 3A, the electrogram lead or conductive element can be deployed through a side opening or window 170 in the sidewall of the elongate body 105. In one embodiment, the window 170 is

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positioned at or near the distal end of an endovascular member. As shown in FIG. 3A, the electrogram lead 135 also serves the purpose of being able to distance the tip 115 or the ultrasound sensor 121 of the endovascular member away from the inner wall of the blood vessel. In this way, the endovascular electrogram lead is adapted for use to move the ultrasound sensor away from a blood vessel wall.

The deployed shape of the electrogram lead 135 shown in FIG. 3A may include shapes that curve completely or partially about the elongate body 105 and may be positioned proximal to the distal end, span the distal end or be positioned distal to the distal end. In one aspect the electrogram lead 135 is formed from a shape memory metal or material that is appropriately pre-set into the desired deployed shape. In one embodiment, the endovascular lead 130 is made of nitinol. The endovascular lead 130 may also include an atraumatic tip 139. The atraumatic tip 139 may be formed from the electrogram lead (a curved end, shaped end or rounded end) or may be a separate structure attached to the distal end to provide the atraumatic capability.

The endovascular electrogram 130 may be used to perform a number of additional and optional functions. As shown in FIG. 3B, when the endovascular electrogram lead is in the stowed condition, the lead curves the distal end 115. In this configuration, a steering element (such as those shown in FIGS. 4A and 4B) may be used to turn, twist or apply torque to the elongate body using the endovascular lead 130. In this way, the endovascular electrogram lead 130 may also be used for steering, placement or other guidance requirements of the user.

FIGS. 4A and 4B illustrate alternative exemplary embodiments of an endovascular device referred to as a sensor core assembly. The sensor core assembly derives its name from the compact size that allows it to be inserted into or ride along with within a lumen on or in another endovascular device. In this way, the functionality and advantages of the systems and methods described herein may be applied to a wide variety of devices positioned within or used within the vasculature. As such, the sensor core assembly can be pre-inserted (if used for guidance and initial placement) or later inserted (if used for position confirmation) into one of the lumens (inside or alongside) of another endovascular device, e.g. in into a PICC catheter.

The endovascular devices illustrated in FIGS. 4A and 4B also illustrate a steering element 153 on the proximal end. The steering element may be used to rotate one or both of the elongate body, a steering element in the elongate body or an electrogram lead 130 configured for concurrent use as a steering element. In use, the user would grasp the steering element 153 and manipulate as needed to produce the desired movement of the elongate body, the distal tip or the endovascular device. The steering mechanism 153 and the endovascular lead 130 may also be sized and configured that the lead, turned by the steering mechanism may apply torque or impart rotation to the elongate body or otherwise facilitate manipulation, steering or control of the endovascular device.

The embodiments illustrated in FIGS. 4A and 4B illustrate a connector or hub 154 on the proximal end that provides an appropriate and consolidated connection point for the sensors and other components of the endovascular device to the guidance system 100. The connector 154 and steering device 153 may be adapted and configured to allow relative movement between them so that the steering element 153 may be used without interrupting the connectivity provided by the connector 154.

FIG. 4C is a conventional catheter 90 with a body, a distal end 95, a catheter hub 97 on the proximal end. A lumen 96



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extends from the distal end, though the body and hub into communication with the tubes **92** and fittings **91a**, **91b**. The endovascular device **150** (FIGS. **4A** and **4B**) may be inserted directly into the patient vasculature and guided as described herein to a target site. Thereafter, the catheter **90** (or other device for placement) is run over the device **150** until in the desired position. Alternatively, the endovascular device **150** or sensor core assembly can be inserted in the lumen of an endovascular device (lumen **96** of catheter **90**) which is then inserted into the patient's body and guided based on sensor inputs from the endovascular device **150**.

In another aspect, the elongate body **105** is itself conductive using a metal wire or has integrated a conductive element such that it can detect electrical activity of the body and transmit resulting electrical signals to the proximal end of the member. The proximal end of the conductive element can be attached to a system for signal processing and graphical user interface. The attachments for the various sensors and components of the endovascular device **150** may be wired or wireless connections may be used.

FIG. **5B** illustrates an endovascular device **150b** with an elongate body **105** with a proximal end and a distal end. There is a non-imaging ultrasound transducer on the elongate body **120** and an endovascular electrogram lead on the elongate body in a position that, when the endovascular device is in the vasculature, the endovascular electrogram lead is in contact with blood. In this embodiment, the elongate body **105** comprises a coated metal braided structure **172** as best seen in the cut away portion of FIG. **5B**. There is a coating **159** (typically an insulating coating may of a biocompatible polymer) over the metallic or conductive braided structure **172**. A portion of the coating **159** on the metal braided structure **172** is removed (providing a window **170**). The exposed metal braided structure (i.e., that portion exposed in window **170**) functions as an endovascular electrogram lead electrical sensing segment **135**. The remained of the braid **172** functions as the lead to transmit the signals detected by the exposed section back to the processor or other components of the guidance system **100**.

Alternatively, as shown in FIG. **5B**, the tube may be metallic or metal braid encapsulated by polymeric material. Additionally or alternatively, a polymeric material like PTFE or polyimide and a polymeric compound, e.g., polyimide and graphite or glass fiber can be used. A separate structure such as a spring, a wire or a mesh wire, made with stainless steel or nitinol for example, may also be inserted into or formed within the inner lumen of the sensor core tube to provide additional column strength and resistance to kinking or extreme bending to the sensor core tube. In addition, the separate wire can also be used for conducting electrical signals generated by the patient. FIGS. **5A** and **5B** demonstrate examples of these designs.

In the embodiments illustrated in FIGS. **5A** and **5B**, the sensor core assembly may contain a polymeric tube **159**. The outer diameter of the tube may be from 0.010" to 0.030", the inner diameter from 0.008" to 0.028". The polymeric tube may be coated, for example with PTFE. The transducer, which can be 0.010" to 0.030" in diameter is fixed at the distal end of the sensor core assembly with Doppler-transparent adhesive or epoxy which can also be used as a lens or a plurality of microlenses to optimize the ultrasound beam profile.

At the distal end close to the transducer, there may be one or multiple windows **170** or a skived openings of 1 to 5 mm in length and width each that provides the ability for an electrogram element, e.g. the separate wire, to be in direct contact with biological fluid, blood, or tissue. The separate wire or

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electrogram lead can be made with any conductive material, e.g., nitinol, stainless steel, and is suitably connected to transmit detected electrical signals to the proximal end of the sensor core assembly and to components of guidance system **100**. The separate wire may consist of one continuous conductive element or several conductive elements that are connected together.

In the embodiment in FIG. **5B** the conductive element **130/135** is provided by a braid which is used to reinforce the shaft of the endovascular device. The braid can be made of any conductive material, e.g., stainless steel or nitinol, and can have any kind of geometries and number of wires. The braid is exposed at the distal end of the endovascular device to allow contact with blood and therefore be capable of detecting electrical activity. In some embodiments the braid serves as a reinforcement layer and therefore is electrically isolated from both the inner and the outer sides. In another embodiment, the tubing used for sensor core assembly can be made with a sleeve which has a mesh in a braid or coil form encapsulated by polymeric material. The sleeve may or may not have a polymeric material only stem at its ends. The mesh can be made with any conductive material, such as Nitinol or stainless steel, and needs to be able to transmit electric signal from the distal end to the proximal end of the sensor core assembly. The mesh may consist of one or multiple types of conductive elements and can be made with one or multiple conductive or non-conductive materials. The mesh may also consist of one or multiple types of continuous conductive element or several conductive elements that are connected to each other. By removing some of the polymeric material and exposing the conductive mesh to biological fluid, blood or tissue, endovascular electrogram signal can be transmitted through the mesh and the system can receive and interpret the signals. A separate polymeric sleeve or other isolating material can be used to isolate the wire attached to the Doppler sensor (coaxial or twisted pair wire or grounded twisted pair wire or any other type of conductive element) from contact with biological fluid, blood or tissue. A Doppler-transparent atraumatic tip can also be added to the distal end of the sensor core assembly. The Doppler-transparent atraumatic tip can also be used as a beam-shaping element for the ultrasound beam.

#### Endovascular Access and Guidance System

##### System Architecture

FIG. **6** illustrates a system **100** that can be used to guide catheter placement using non-imaging ultrasound based blood flow information and electrical activity of the body. In one particular example, the system **100** is used to place an endovascular device **150** in the superior vena cava **14** using blood flow and ECG patterns and relative to the sinoatrial node **8** using intravascular ECG. An exemplary display **140** and/or user interface is shown in FIGS. **7**, **8**, **9**, **13**, **14A** and **14D** and is described below.

Returning to FIG. **6**, the system **100** integrates a data acquisition system, two DAQ cards, an isolation transformer and a computing platform, e.g., a PC which has software loaded to process the signals and display information on a screen. The data acquisition system and the PC are powered from a common Isolation Transformer or other suitable power supply. The data acquisition system (**1**) is capable of acquiring ultrasound signals and electrical signals generated by the body activity, such as electrogram (ECG, EEG and/or EMG) including intravascular and intracardiac electrocardiogram signals. A sensor-based endovascular device **150** as described herein can be connected to the data acquisition system (**1**). An



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additional ECG lead **112** can be attached to the patient's skin (see FIG. **1**) or provided by lead **130/135** for collecting a reference signal. The optional speaker (**11**) is used to optionally convert Doppler frequencies, i.e., blood velocities into audible signals or to otherwise provide signals or instructions to inform a user of the position of the device **150**. One analog-to-digital converter (**8**) is used to digitize ultrasound signal information and transfer it to the processor **140** or other suitable computing platform for processing. A second analog-to-digital converter (**9**) is used to digitize electrogram signals coming from the electrogram lead on the endovascular device and from the reference electrode (either outside or inside the vasculature). Other or additional A/D converters may be provided based on the sensors used in the device **150**.

The computing platform (**4**) can be a generic one like a personal computer or a dedicated one containing digital signal processors (DSP). The computing platform serves two purposes. It provides the processing capabilities of the processor **140** that allows data processing algorithms (**5**) to run. The various data processing algorithms employed by the various methods of embodiments of the current invention are described in greater detail below. The other purpose of the computing platform is to provide "back-end" functionality to the system **100** including graphical user interface, data storage, archiving and retrieval, and interfaces to other systems, e.g., printers, optional monitors (**10**), loudspeakers, networks, etc. Such interfaces can be connected in a wired or wireless configuration. Those of ordinary skill will appreciate that the conventional components, their configurations, their interoperability and their functionality may be modified to provide the signal processing and data capabilities of the guidance system **100**.

FIG. **19** illustrates more detail of the functional blocks of an exemplary Data Acquisition System **1** (from FIG. **6**). These components are those found in conventional ultrasound systems.

The signal flow path illustrated and described with regard to FIG. **19** details how two different physiological parameters may be sampled, acquired and digitalized for processing according to the methods and systems described herein. While FIG. **19** may specific reference to ECG and Doppler, it is to be appreciated that the acquisition, conversion, processing and correlation described herein may be applied generally to ultrasound and electrogram signal combinations including a variety of different ultrasound modes and various different types of sources of electrogram signals. Moreover, ablation, acquisition, conversion, processing and correlation steps, components and capabilities may be included in the system **100** as needed depending upon the type and number of sensors employed on the endovascular device **150**.

Returning to FIG. **19**, the ultrasound transducer (TXD) **120** which can be driven as Doppler and A-mode imaging is attached to a transmit/receive (T/R) switch to support pulsed wave operation. In some configurations, the connection between transducer and system may be optically isolated. The Pulser block generates the ultrasound signal used to drive the transducer **120**. Exemplary signals are between 7-14 MHz. The Tx pulser table is firmware which allows the system to define the exact shape of the pulse train generated by the Pulser. The Programmable Gain (TGC) block implements variable gain, in particular useful for time-depth gain compensation. The Analog Filter (BPF) is a band-pass filter used to filter out unwanted high and low frequency signals, e.g., noise and harmonics. The Rx Gate and TGC Control block is used to select the sample volume range (depth) and width, i.e., the target volume from where the incoming (i.e. reflected) ultrasound signals are acquired. In the case of Doppler, the

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sample volume range (depth) and width defines the blood pool volume which is analyzed for velocity information. In the case of A-mode acquisition, the range extends from the transducer face to the entire available depth of penetration, and maximum width. In addition the Rx Gate and TGC Control is used to control the TGC block for the appropriate values with respect to the range and width of the sample volume. The ADC block converts the incoming analog signal into digital signal. Typical values for the high frequency A/D conversion are 12 bit depth of conversion and more than 100 MHz conversion rate. The FIFO block contains ultrasound digitized data corresponding to the sample volume as selected by the Rx Gate and TGC control block. The System Interface block (CPU) allows for the following functional blocks to be programmed algorithmically or by the user via a general purpose computer (CPU): Tx Pulse and Pulser Table, Rx Gate and TGC Control, and the Cos/Sin Table. The Cos/Sin Table is a building block that is used for the quadrature demodulation of the high frequency signal. The quadrature demodulation Cos/Sin table can be implemented either in software as a DSP (digital signal processor) function or as firmware in an FPGA (field programmable gate array). The Mixer multiplies the incoming signal with quadrature cos and sin signals to obtain 90 degrees phase shifted signals which allow for extracting the Doppler frequency shift from the incoming signal. The Mixer block can be implemented either as a DSP or an FPGA function. The FIR (finite impulse response) filter is used to filter the directional Doppler signals. An interface is provided to transfer digital ultrasound and electrogram (or other sensor) information to the host computer (CPU). The interface can interface either as a standard USB interface (shown in FIG. **19**), as a network interface using TCP/IP protocols or any other kind of digital bidirectional real-time interface. The Power Regulators & Battery Charger provides power to the Acquisition System and charge the batteries in a battery-powered configuration. The Battery Monitor & Control block provides the interface (control and monitor) of the battery and power by the host computer (CPU). IN this example, the electrogram signal path consists of two connectors to the endovascular device (leads **130/135**) and/or a reference lead **112**, as needed. The connectors may be optically isolated for patient safety. The ECG block consists of an amplifier of ECG signals powered by the Isolated Power Supply. The ADC digitizes the ECG signal with 8 to 12 bits at a sampling rate of 100 Hz to 1 KHz.

FIG. **20** illustrates an exemplary software block diagram **4** (FIG. **6**) for providing the processing capabilities used by embodiments of the present invention. The main software application consists of several real-time threads running concurrently on the host computer platform. The ACQ Universal Lib Agents controls the acquisition of Doppler and ECG data. The Data Transfer Thread distributes the data to the ECG Algorithm Thread, the Doppler Algorithm Thread and the File Writer Thread. The Data Transfer Thread also ensures synchronization between the ECG and the Doppler data streams, such that, for example, ECG gated/synchronized Doppler analysis can be implemented. The File Writer Thread streams unprocessed real-time Doppler and ECG data to a storage device, e.g., hard disk. The benefit of this approach is, that in playback mode, i.e., when reading data from the storage medium through the File Writer Thread, the data can be processed at a later time exactly the same way it was processed at acquisition time. The ECG and Doppler Algorithm Threads implement real-time feature extraction and decision making algorithms as describes herein.

The ECG and Doppler Display Threads display ECG and Doppler information on the graphical user interface (GUI) in

real-time. The Main GUI Thread is responsible for user interaction, system settings, and thread and process synchronization and control. In the embodiment illustrated in FIG. 20, the software applications interact with a number of other components. An operating system, e.g., Windows, Linux, or a real-time embedded operating system, e.g. VxWorks provides the infrastructure for the application to run and a number of services, e.g., interface to a database for patient data repository. The ACQ Universal Library provides software functions which control the data acquisition hardware. The ACQ USB Driver or a TCP/IP network driver or any other kind of communication driver controls the communication channel between the Acquisition System (Module) and the host computer platform. Through this bidirectional communication channel Doppler and ECG information is transferred from the ACQ Module and control information is transferred towards the ACQ Module.

#### Algorithms

In one embodiment, the system according to the current invention uses two types of physiological parameters detected by the sensor-based endovascular device 150 in order to determine the location of the endovascular device 150 in the vasculature. In the examples that follow, the parameters are ultrasound determined blood flow patterns and intravascular electrocardiogram patterns. FIGS. 7, 8, and 9 are views of a display 130 that illustrate blood flow and electrocardiogram patterns at different locations in the vasculature.

The display 130 illustrated in FIGS. 7, 8 and 9 includes: a flow velocity profile output 705; a bar graph 710; a plurality of indicators 715; and an electrogram output 720. The flow velocity profile output 705 includes a curve 725 related to the flow away from the sensor and a curve 730 related to the flow towards the sensor. The relative power of these flows towards and away are reflected in the bar graph 710. The bar graph 710 has an indication 740 for flow towards the ultrasound sensor and an indication 735 for flow away from the ultrasound sensor. The bar graph 710 may be color coded. One color scheme would represent flow away as green and flow towards as red. Based on the processing performed as described herein, the system is able to determine several different states or conditions for the endovascular device 150. The indicators 715 are used to represent these conditions to a user viewing the display 140. One indicator may be used to represent movement of the device 150 in the desired direction. In the illustrative embodiment, the arrow 745, when illuminated, indicates proper direction of flow. The indicator may be color coded, such as green. One indicator may be used to represent improper or undesired movement of the device 150. In the illustrated embodiment, the octagon shape 750 when illuminated, indicates direction to travel in an undesired direction. This indication may be color coded red. Another indication may be provided to indicate to the user that the system cannot determine or is unsure about device 150 position or movement. The triangle 755 is used for this indication. This indicator may be color coded yellow. Another indicator may be used to inform a user that the system has determined that the device 150 is in a position where the sensors on the device are detecting signals of the target location when the system detects, for example, blood flow patterns and electrogram signals of the target location, the indicator 760 is activated. Here, the indicator 760 is one or more concentric rings representing bullseye. This indicator may also be color coded, such as with the color blue. The electrogram output 720 displays the electrogram signals detected by the electrogram leads used by the system. The outputs displayed each of FIGS. 7, 8 and 9 correspond to actual data and results obtained using a device and system as described herein. For

comparison, each of the ECG displays 720 are the same scale to facilitate comparison of the ECG wave from at each position. Similarly, the flow curves 725, 730 (and corresponding relative sizes of the bar graph indications 735, 740) are also representative of actual data collected using the devices and techniques described herein.

The display 130 illustrated in FIGS. 7, 8 and 9 includes a flow velocity profile 705 bar graph 710, indicators 715 and an electrogram output 720.

FIG. 7 illustrates the blood flow velocity profile (705), the intravascular ECG (770), indicator 715 (with 745 illuminated) and bar graph 710 when the tip of the endovascular device 150 is in or moving with venous flow towards the superior vena cava (SVC).

When the device moves with the venous flow towards the heart, the blood flow away from the sensor dominates the blood flow towards the sensor as shown by the relative position of curves 725 and 730 and bar graphs 735, 740. The ECG 770 in FIG. 7 illustrates the typical base line ECG expected in most locations when the device 150 is away from the heart.

FIG. 8 illustrates the blood flow velocity profile (705), the intravascular ECG (770), indicator 760 and bar graph 740 when the tip of the endovascular device at the caval-atrial junction. When the device 150 is positioned at a target location, correlation of the various unique signatures of the target location may be used to add confidence to the device position. When the device is at a target site near caval-atrial junction then the blood flow toward/away from the sensor are nearly balanced because of the flows converging from the superior vena cava of the inferior vena cava. This nearly equivalent flow toward/away is represented by the proximity of the curves 725/730 as well as bars 735/740. Importantly, the ECG 770 indicates the prominent P-wave that indicates proximity of the ECG lead to the SA mode. The presence of the larger P-wave is an example of a physiological parameter that is used to correlate the flow information and confirm device placement.

FIG. 9 illustrates the blood flow velocity profile (705), the intravascular ECG (770), indicator 715 and bar graph 710 when the tip of the endovascular device is in the internal jugular vein. When the endovascular device 150 enters the jugular, the flow towards the sensor now dominates the velocity profile as reflected in the relative positions of the curves 730, 725 and the bars 735, 740 in bar graph 710. Additionally, the ECG wave demonstrates a unique QRS polarity (i.e., the QRS complex is nearly equal negative and positive). This distinctive ECG profile is used to confirm that the device 150 has entered the jugular vein. Criteria for feature extraction and location identification can be developed for both the time and the frequency domain as well as for other relationships that exist between criteria in time vs. frequency domains.

FIG. 21 illustrates the flow chart 800 implementing an exemplary algorithm according to one aspect of the present invention. First, at step 805, Doppler and electrocardiogram/ECG (ECO) signals are sampled at the desired frequency, typically between 20 to 50 KHz/channel for the Doppler data and 100 Hz to 1 KHz for the ECG data. Next, at step 810, the ECG (ECO) and Doppler data are transferred to the host computer memory. Next, at step 815, Doppler directional data (antegrade and retrograde or left and right channel) and ECG data are separated at different memory locations since they come packed together in the incoming data stream from the sampler. Next, at step 820, the three data streams (Doppler antegrade, Doppler retrograde, and ECG) are streamed to the storage in sync. Next, at step 830, the algorithms identifies the R-peak in the ECG data stream and then locates the P-wave segment within 400 to 600 ms to the left of the R-peak. If the

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answer to block 840 is yes, then the ECG/ECO data is then appended to the display buffer (step 845) and plotted on the graphical user interface (step 850). If the answer in block 840 is no, then the Doppler data corresponding to a desired period in the heart beat, e.g., during the P-wave, during the QRS-complex, or during the entire heart beat is processed as in steps 855, 860 and 865 through FFT and filters and further described below. Based on the results of processing, blood flow direction and tip location information about the endo-vascular sensor-based device is presented on the display and the Doppler information is plotted on the display.

In general, software controls to algorithms can be applied to the frequency domain after performing a Fast Fourier Transform (FFT) or in the time domain (No FFT). Typical number of points for the FFT are 512, 1024, 2048, 4096. These numbers represent the length of a data vector. The signal can be averaged over time or over the number of samples both in time and frequency domains. The on-line averaging uses a filter window of variable length (between 3 and 25 samples) to average along a data vector. The multi-lines averaging computes the average of a selectable numbers of data vectors. The can spectral power can be computed in frequency domain from the shape of the power spectrum for each of the considered signals (directional Doppler and ECG). The spectral power of the directional Doppler spectra is used to differentiate between retrograde and antegrade blood flow. Selective filtering of certain frequencies is used to remove undesired artifacts and frequency components, e.g., high frequencies indicative of a high degree of turbulence. Selective filtering also offers the ability to look consider certain frequencies as being more important than other in the decision making process. For example the lowest and the highest relevant frequency of the spectrum, i.e., the lowest and the highest relevant detected blood velocity can be associated to certain location in the vasculature and in the blood stream. Threshold values are used to make decisions regarding the predominant flow direction and the presence of the QRS-complex or the P-wave. The threshold values can be computed using an auto-adaptive approach, i.e., by maintaining a history buffer for data and analyzing tendencies and temporal behavior over the entire duration of the history data buffer.

Criteria useful in assessing location in the vasculature based on ultrasound and ECG information are described below. Some of the criteria which can be used to determine sensor location in the vasculature from the blood flow velocity profiles are: a) comparing energy, for example as measured by spectral power in frequency domain, of each of the directions of bidirectional flow; b) bidirectional flow patterns in lower velocity range to detect the caval-atrial junction; c) pulsatility to detect atrial activity; d) the highest meaningful average velocity of the velocity profile and others described herein.

Some of the criteria which can be used to determine sensor location in the vasculature from the intravascular ECG are: a) peak-to-peak amplitude changes of the QRS complex or of the R-wave; b) P-wave relative changes; c) changes in the amplitude of the P-wave relative to the amplitude of the QRS complex or of the R-wave; and others as described herein. The correlation between the shape of the intravascular ECG waveforms and the shape of the blood flow velocity profile as well as the correlation between the relative changes of the two can also be used as criteria for determining positioning, guiding or confirming sensor location in the vasculature.

Returning to FIGS. 7, 8 and 9, in display 705, the horizontal axis represents the Doppler frequency shift proportional to the blood velocity and the vertical axis the amplitude of a

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certain frequency, i.e., the power (or energy) or how much blood flows at that particular velocity (frequency). The curve 725 illustrates the velocity distribution at the Doppler sensor location of blood flowing away from the sensor. The curve 730 illustrates the velocity distribution at the Doppler sensor location of blood flowing towards the sensor. Typically, the curve 725 is green and the curve 730 is red for applications where the desired movement is towards the heart. Other color codes could be used for a different vascular target. For the color-blind, directions of flow can be indicated using symbols other than colors, e.g., '+' may indicate flow away from the sensor and '-' may indicate flow towards the sensor, or numbers may indicate strength of flow. Scrollbars can also be used to indicate intensity of bidirectional flow. Bar graphs 710, 735, 740 may also be used. Another way to indicate direction of flow and to identify certain flow patterns to the user is by using audible signals, each signal being indicative of a certain flow, or in general, of tip location condition. A green arrow (745), a green bull's eye (760), or a red stop sign (750) can be used as additional indicators for flow conditions and, in general, to identify the location of the sensor in the vasculature. In ECG 770, the horizontal axis represents time and the vertical axis represents the amplitude of the electrical activity of the heart. The algorithms described herein may be applied to the electrical mapping of the heart activity independent of how the electrical activity was recorded. Devices described herein may record intravascular and intracardiac ECG. Other methods of recording ECG, for example using a commercially skin ECG monitor (such as lead 112 in FIG. 1), are also possible and may be used as described herein.

Referring again to FIGS. 7, 8 and 9, one criterion used for correlating the Doppler frequency (velocity) distributions to the anatomical locations refers to the spectral power or the area under a specific Doppler frequency curve (the integral computed of the frequency spectrum) in conjunction with the uniformity of differences in frequencies over the entire frequency range. In FIG. 7 the sensor is positioned in the superior vena cava looking towards the heart and with the main blood flow stream moving away from the sensor towards the heart. The green area is larger than the red one and, in this case, the curve 725 is above curve 730 over the whole range of Doppler frequencies (velocities). In FIG. 9, the catheter tip has been pushed into the jugular vein. The blood is flowing towards the heart and towards the sensor located at the catheter tip. The area under the red curve 730 is larger than the area under the green curve 725 and the velocities in red (towards the sensor) are larger than the velocities in green over the entire range of velocities in this case. In each of FIGS. 7 and 9, the bar graph 710 indicates as well as the relative sizes of flow towards and away from the sensor. Consequently, if the blood velocity profile shows larger spectral power in one direction it is inferred that this is the predominant direction of flow of the blood stream.

Another criterion is related to the distribution of the low velocities in the two directions (i.e., towards and away from the sensor). In a vein, the blood velocities are different than, for example in the right atrium. Therefore most of the relevant spectral energy will be present in the low velocity range. Typically, low blood flow velocity range is from 2 cm/sec to 25 cm/sec.

Another criterion is the similarity between the green (toward) and the red (away) curves. At the caval-atrial junction (FIG. 8) the green and red curves are almost identical with similar areas (similar energy or the area under curves 725/730) and with similar velocity distributions (similar velocity profiles or shape of the curves 725, 730). This is indicative of the similar inferior vena cava (IVC) and superior vena cava

(SVC) flow streams joining together from opposite directions when entering the right atrium.

Another criterion is the behavior in time of the flow patterns and signatures. In particular the behavior refers to the difference between strongly pulsatile flow present in the right atrium, in the heart in general as well as in the arterial flow compared to the low pulsatility characteristic of venous flow.

Another criterion takes into account a periodic change in behavior of the flow profiles with the heart rate. A stronger periodic change with the heart rate or pulsatility is indicative of the right-atrial activity.

Another criterion is the amplitude of the green and red curves. The higher the amplitude at a certain frequency, the higher the signal energy, i.e., the more blood flows at the velocity corresponding to that particular frequency.

Another criterion is the amplitude of the highest useful velocity contained in the green and red velocity profiles. Useful velocity is defined as one being at least 3 dB above the noise floor and showing at least 3 dB of separation between directions (green and red curves). The highest useful velocity according to the current invention is an indication of the highest average velocity of the blood stream because the device according to the present invention intends to measure volumetric (average) velocities.

Another criterion is the temporal behavior of the velocity profiles at a certain tip location. If the tip location is further away from the heart, e.g., in the internal jugular vein, then the predominant temporal behavior may be pulsatility due to respiration of the main blood stream. FIG. 11 represents exemplary flow patterns based on this concept. In the internal jugular vein the main blood stream is represented by the red curve (blood flows against the sensor). Closer to the heart and in particular in the right atrium, the predominant temporal behavior is pulsatility related to the heart beat.

Another criterion is related to the absolute and relative changes of the P-wave at different locations within the vasculature. As represented by ECG 770 in FIGS. 7, 8 and 9, the P-wave dramatically increases at the caval-atrial junction (FIG. 8) when compared to the P-wave in the superior vena cava (FIG. 7) or the internal jugular vein (FIG. 9). Additional criterion relate to the P-wave relative amplitude when compared to the QRS complex and the R-wave.

FIG. 12 illustrates that even in the case of patients with atrial fibrillation, the atrial electrical activity, which may not be seen on the regular skin ECG becomes visible and relevant as the intravascular ECG sensor approaches the caval-atrial junction. Both the amplitude of the atrial electrical activity and its relative amplitude vs. the QRS and R-waves change visibly at the caval-atrial junction in the close proximity of the sino-atrial node.

With reference again to FIGS. 7, 8 and 9, another criterion is related to the absolute and relative changes of the QRS complex and the R-wave at different locations. The R-wave and the QRS complex dramatically increase at the caval-atrial junction (FIG. 8) when compared to the waveforms in the superior vena cava (FIG. 7) or the internal jugular vein (FIG. 9). Its relative amplitude to the P-wave also changes dramatically. FIG. 12 shows that even in the case of patients with atrial fibrillation, the R-wave and the QRS complex change significantly as the intravascular ECG sensor approaches the caval-atrial junction. Both the amplitude of the R-wave and QRS complex and their relative amplitude vs. the P-waves change visibly at the caval-atrial junction in the close proximity of the sino-atrial node.

Any individual criterion and any combination of the above criteria may be used to estimate location in the vasculature. A

database of patterns can be used to match curves to anatomical locations instead of or in addition to applying the above criteria individually.

FIG. 10 illustrates how the endovascular electrical signal can be used to trigger and gate the processing of the ultrasound signals. The electrical signal acquired from the endovascular sensor is periodic and related to the heart cycle (10a). It is similar in shape with a known diagnostic ECG signal. By analyzing the waveforms, e.g., P-wave, QRS complex and the T-wave, a number of events and time segments can be defined in the heart cycle. The P-wave event occurs when the P-wave amplitude is at its peak. The R-wave event occurs when the R-wave amplitude is at its peak. Other events can be defined, e.g., when the R-wave amplitude is one third lower than the peak. Between such events time intervals can be defined. T1 is the time interval between 2 consecutive P-waves and indicates the heart rate. T2 is the time interval between two R-waves and similarly indicates the heart rate. T3 is the time interval between the P and the R waves. T4 is the time interval between the R-wave and the subsequent P-wave. Other time intervals can be defined, as well. These intervals can be defined in reference to a peak value of a wave, the beginning or end of such a wave, or any other relevant change in the electric signal. The events defined in a heart cycle can be used to trigger selective acquisition and/or processing of physiological parameters through the different sensors, e.g., blood flow velocity information through the Doppler sensor. The time intervals can be used to gate the acquisition and processing of physiological parameters like blood velocity, e.g., only in the systole or only in the diastole. Thus more accurate results can be provided for guiding using physiological parameters. Graphs 10b and 10c illustrate exemplary ultrasound data triggered on the T3 interval.

FIG. 11 illustrates how the variations in blood flow as identified by the Doppler signal can be used to trigger and gate signal acquisition and processing based on the respiratory activity of the patient. The flow patterns as indicated by the Doppler power spectrum change with the patient's respirations. Certain cardiac conditions like regurgitation also cause changes in the flow patterns with respiration. Such changes with respirations can be identified, in particular when the strength of a certain pattern changes with respirations. These identified changes can then be used to trigger and gate the acquisition and processing of physiological parameters relative to the respiratory activity of the patient. Thus more accurate results can be provided for guiding using physiological parameters.

FIG. 12 illustrates how the relative changes in the QRS complex can be used to identify proximity of the sinoatrial node even in patients with atrial fibrillation, i.e., patients without a significant P-wave detected by diagnostic ECG. In patients with atrial fibrillation, the P-wave cannot be typically seen with current diagnostic ECG systems (see (1)). Still changes, i.e., significant increases in the QRS complex amplitude as identified by an endovascular sensor are indicative of the proximity of the sino-atrial node (See (2)). In addition, an endovascular device can measure electrical activity which is not detected by a standard ECG system, e.g., the atrial electrical activity in a patient thought to have atrial fibrillation (See (3)). Such changes in the waveform of the endovascular electrical signal can be used to position the sensor and the associated endovascular device at desired distances with respect to the sino-atrial node including in the lower third of the superior vena cava or in the right atrium.

Graphical User Interface

FIG. 13 illustrates elements of an exemplary display 130 configured as a graphical user interface (GUI) for a vascular

access and guidance system as described herein. The display **130** in FIG. **13** integrates in a user-friendly way different guiding technologies for vascular access: Doppler, ECG, audio, workflow optimization, A-Mode imaging, for example. The Doppler window presents the characteristics of the blood flow as detected using Doppler or cross-correlation methods. The information can be presented in either the time or the frequency domain. In the case of bidirectional Doppler, the two directions can be represented on a single display or on two different displays. Several Doppler windows can be stacked and accessed through tabs in order to either provide a history of the case or to access a template database. Alternatively the history/template window can be displayed separately on the instrument screen. The A-Mode Imaging window presents ultrasound information in a graph of time (x dimension) version depth (y dimension). The window gets updated regularly such that the movement of the hand holding the A-Mode imaging device appears to be in real-time. This increases the ability of hand-eye coordination. Typically the origin of an A-mode single beam is on top the screen and the A-Mode ultrasound flash light is looking down. Another use for the A-Mode imaging display window is to allow for imaging and identification of blood clots. The Guiding Signs window consists of colored elements of different shapes that can be turned on and off. For example when the Doppler window displays a much larger curve than a red one, then the green light in the Guiding Signs window is turned on and all other lights are turned off. The red light on (and the others off) indicated that the endovascular sensor is pointing in the wrong direction. A yellow light on indicates that the signal is not strong/clear enough to make a determination. The blue light on indicates that the sensor senses blood flow characteristic of the caval-atrial junction.

The ECG window displays electrical signals detected by the endovascular probe. The window can display single or multiple electrical signals and one or more ECG windows may be displayed. The programmable function keys are shortcuts to different system functions. They can be accessed through the touch screen or remotely via a remote control. Typical function keys would select screen configurations and system functions or would provide access to default settings. The Audio window presents either the Doppler or the audio information received from the endovascular sensor. In a preferred embodiment the audio window is similar to the interface of a digital audio recorder showing the intensity of the channels (flow away and towards the probe) on simulated LED bars of potentially different colors. For the color blind numbers are also displayed showing the average intensity of flow in each direction. Alternatively, a single LED bar can be used, such that the different blood flow intensity in each direction is shown at the two extremities of the single LED bar potentially in different colors. The System Control Unit provides control over the data acquisition devices, system settings, information processing, display and archiving. Any combinations of the above described windows are possible and each window type can have multiple instances.

Display windows can be repositioned and resized, displayed or hidden. The screen layout is user configurable and user preferences can be selected and archived through the System Control Window. The System Control Window can display an alphanumeric keyboard which can be used through the touch screen. Character recognition capabilities can facilitate input using a pen. A touch screen enables the user to directly access all the displayed elements. The loudspeakers are used for the sound generated either by the Doppler or by auscultation components. The sound system provides for stereo sound and alternatively headphones can be used. In the

case of Doppler information, the audible Doppler frequency shift corresponding to one blood flow direction, e.g., towards the probe can be heard on one of the stereo speakers or headphones, e.g., the left channel. At the same time, the audible Doppler frequency shift corresponding to the other blood flow direction, e.g., away from the sensor can be heard on the other of the stereo speakers or headphones, e.g., the right channel.

The system can be remotely controlled, networked or can transfer information through a wireless interface. An RFID and/or barcode reader allows the system to store and organize information from devices with RFID and/or barcode capability. Such information can be coordinated with a central location via, for example, a wireless network.

In many clinical applications, endovascular devices are required to have the device tip (distal end) to be placed at a specified location in the vasculature. For example CVC and PICC lines are required to have their tip placed in the lower third of the superior vena cava. However, for example due to lack of a guidance system at the patient's bedside, users currently place the catheters into the patient's body blindly, often relying on x-ray to confirm the location of the catheter a couple of hours after initial placement. Since the CVC or a PICC line can be released for use only after tip location confirmation, the patient treatment is delayed until after X-ray confirmation has been obtained. Ideally, users should be able to place the catheter at the desired location with high certainty and with immediate confirmation of tip location. Building a user-friendly, easy-to-use system which integrates electrical activity information with other types of guiding information, devices and techniques described herein.

FIG. **14** provides exemplary display **140** with an easy to use graphical user interface which combines location information from the different sensors and displays graphical symbols related to the location of the endovascular device. For example, if the endovascular device is advancing towards the caval-atrial junction a green arrow and/or a heart icon are displayed together with a specific audible sound as shown in FIG. **14B**. If the endovascular device is advancing away from the caval-atrial junction then a red stop sign and/or a red dotted line are displayed together with a different specific audible sound as shown in FIG. **14C** or **14D**. If the tip of the endovascular device is at the caval-atrial junction then a blue or green circle or "bull's eye" is displayed together with a different specific audible sound as shown in FIG. **14A**. Of course, any colors, icons, and sounds or any other kind of graphical, alphanumeric, and/or audible elements can be used to indicate the tip location.

While the simplified user interface is displayed all the underlying information (Doppler, ECG, and others) can be digitally recorded so that it can be used to print a report for the patient's chart. Storing of patient information, exporting the data to a standard medium like a memory stick and printing this information to a regular printer are especially useful when the device and system disclosed in the current invention are used without chest X-ray confirmation to document placement at the caval-atrial junction of the endovascular device.

#### Ultrasound and ECG Methods of Positioning Guided Endovascular Devices

FIG. **15** illustrates an exemplary method **300** of catheter placement. In this example, the method **300** describes how a user would place a PICC catheter using a guided vascular device with guidance information provided using blood flow information and ECG signals provided by the system and processing techniques described in greater detail in the cur-

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rent invention. This example is for illustration purposes only. Similar conventional catheter, guide wire or device introduction procedures, may be tailored for the requirements of other therapeutic devices such as, for example, for placement of hemodialysis catheters as well as for the placement of laser, RF, and other catheters for percutaneous treatment of varicose veins, among others described in greater detail below. The progress of the device through the vasculature 4 the signals produced by the system will also be described with reference to FIG. 16.

While the techniques described herein may be practiced in a number of clinical settings, the placement method 300 will be described for bedside catheter placement. The workflow presented in catheter placement method 300 begins with step 305 to measure approximate needed length of catheter. This step is recommended in order to verify the location indicated by the apparatus. This step is currently performed by the medical professional in the beginning of the procedure.

Next, at step 310, unpack sterile catheter with placement wire inserted and the sensor attached. In a preferred embodiment, the packaged catheter already contains a modified stylet with Doppler and ECG sensors. Currently, some PICC catheters are already packaged with stylets which are used by the medical professionals to push the catheter through the vasculature. Unlike the device embodiments of the present invention, conventional catheters and the corresponding stylets do not contain sensors suited to the multi-parameter processes described herein.

Next, at step 315, connect non-sterile user interface housing by bagging it with a sterile bag and piercing it with the connector end of the placement wire. In a preferred embodiment, the catheter containing the stylet with sensor is sterile and disposable while the user interface, control, and signal processing unit is reusable and potentially non-sterile. If the unit is not sterilized and cannot be used in the sterile field, it has to be bagged using a commercially available sterile bag. The catheter is then connected to the user interface unit by piercing the sterile bag with the stylet connector. Alternatively, a sterile cord or cable can be passed off the sterile field and subsequently attached to a non-sterile control unit without having to puncture a bag.

Next, at step 320, press self-test button on the user interface housing and wait to see the green LED blinking. Once the sensor is connected the system can execute a self test protocol to check connection and sensor. Of course, any colors, icons, and sounds or any other kind of graphical, alphanumeric, and/or audible elements can be used to indicate the proper connection.

Next, at step 325, insert catheter into the vessel. This step is similar to the catheter introduction currently performed by medical professionals. One preferred insertion point is the basilic vein 6 as shown in FIG. 16.

Next, at step 330, hold in position until green light stops blinking (e.g., becomes solid green light). Once the catheter is in the vessel, it must be held in position for a few seconds or be slowly pushed forward. This step ensures that the signal processing algorithm can calibrate the data acquisition and pattern recognition to the current patient data. At this step a baseline ECG signal may be recorded and stored in memory. Additionally, the processing system will analyze the sensor data to confirm that the sensor is placed in a vein not an artery.

Next, at step 335, after receiving confirmation from the system that the sensor/catheter has been introduced into a vein, the user may start advancing the catheter and watch the green light to stay on. If the green light is on, it means that blood flows away from the catheter tip. This "green light" indication is the desired indication while advancing the cath-

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eter/sensor to the end position. FIG. 16 shows a correct position of the catheter in the basilic vein marked "Green" and meaning that the green light is on (along the dashed pathway).

Next, at step 340, if the light turns red, stop advancing and pull the catheter back until the light becomes green again. The light turns red when blood flows towards the catheter/sensor instead of away from it. This means that the catheter has been accidentally advanced into the jugular or other vein. In FIG. 16 this positioned is labeled "Red" and the catheter is shown in the internal jugular vein. In this situation the blood stream flowing towards the heart comes towards the device. In this situation the catheter must be pulled back to position labeled "2" in FIG. 16 and re-advanced on the correct path into the SVC. If accidentally the catheter is facing a vessel wall and cannot be advanced, the light turns yellow: position marked "yellow" in FIG. 16. In this situation the catheter must be pulled back until the yellow light is off and the green one is on again.

Next, at step 345, advance while green light on. The user keeps pushing while the catheter/sensor remain on the proper path toward the heart.

Next, at step 350, the user stops advancing when light turns blue. As illustrated in FIG. 16 the light turns blue when the lower third of the SVC has been identified. The light turns blue when the processing system has identified the unique flow pattern or physiological parameters (i.e., unique ECG wave form) corresponding to the targeted placement region. In this illustrative method, the unique nature of the flow signature in the junction of the superior vena cava and the right atrium is identified and the blue indicator light illuminated. Next, at step 355, the user may verify actual length against the initially measured length. This step is used to double check the indication provided by the device and compare against the expected initially measured length for the target position.

Next, at step 360, remove stylet and attached sensor.

Next, at step 360, peel away introducer and then at step 370, secure catheter.

In additional alternative embodiments, there is provided a method for positioning an instrument in the vasculature of a body by processing a reflected ultrasound signal to determine the presence of a signal indicating a position where two or more vessels join. This method may be practiced in any of a wide variety of vascular junctions in both the venous and arterial vasculature. One exemplary position where two or more vessels join occurs where the two or more vessels include a superior vena cava and an inferior vena cava. A second exemplary position where two or more vessels join occurs where the two or more vessels include an inferior vena cava and a renal vein. According to one embodiment of the present invention, there is provided a method for positioning an instrument in the vasculature of a body using the instrument determine a location to secure a device within the vasculature of a body; and securing the device to the body to maintain the device in the location determined by the instrument. After the passage of some period of time (as is common with patients who wear catheters for an extended period of time, the instrument may be used to calculate the current position of the device. Next, using the known original position and the now determined current position, the system can determine if the device has moved from the original position.

It should be understood that various alternatives to the embodiments of the invention described herein may be employed in practicing the invention. For example if the target device position where in the brain for example, then the processing algorithms and outputs could be charged to indicate that movement into the jugular is the correct direction

(green indicator) and that movement towards the heart would be an incorrect direction (red indicator). The system indications and parameters can be altered depending upon the location of and access route taken to various different target sites in the vasculature.

Having described the various components and operability of the inventive endovascular guidance system, numerous methods of endovascular guidance are provided.

In one aspect, the method of positioning an endovascular device in the vasculature of a body is accomplished by advancing the endovascular device into the vasculature and then transmitting a non-imaging ultrasound signal into the vasculature using a non-imaging ultrasound transducer on the endovascular device. Next, there is the step of receiving a reflected ultrasound signal with the non-imaging ultrasound transducer and then detecting an endovascular electrogram signal with a sensor on the endovascular device. Then there is the step of processing the reflected ultrasound signal received by the non-imaging ultrasound transducer and the endovascular electrogram signal detected by the sensor. Finally, there is the step of positioning the endovascular device based on the processing step.

The method of positioning an endovascular device in the vasculature of a body may also include additional or modified steps according to the specific application or process being performed. Numerous additional alternative steps are possible and may be used in a number of combinations to achieve the guidance and positioning results described herein. Additional steps may include verifying that the length of the endovascular device inserted into the body is equivalent to the estimated device length prior to the procedure and/or inputting into the system the length of the endovascular device inserted in the body. Additionally, the step of detecting an endovascular electrogram signal with a sensor positioned on a patient may be added. The sensor may be on the patient or a second or additional sensor on an endovascular device. There may also be added the step of comparing the endovascular electrogram signal from the sensor on the device or patient to the endovascular electrogram signal from the second sensor on the device.

The processing methods and algorithms may also be modified or combined to identify important or unique signatures useful in guidance, localization or correlation. The method may include different or customized software or programming for processing ultrasound and/or electrogram signal information. The processing may include processing of reflected ultrasound signal to identify the caval-atrial junction or to determine the highest average velocity of a velocity profile. The processing may include processing of the endovascular electrogram signal to determine: peak to peak amplitude changes in an electrogram complex; peak to peak amplitude changes of an QRS complex in an electrocardiogram; peak to peak amplitude changes of an R-wave in an electrocardiogram and or peak to peak amplitude changes of an P-wave in an electrocardiogram and, additionally or alternatively, to use electrogram information as a trigger to acquire and/or process ultrasound information.

The processing methods and algorithms may also be modified or combined to identify important or unique signatures to determine the position of a guided endovascular device relative to anatomical structures or positions in the body. Examples of these methods include performing the processing step to determine the position of the endovascular device relative to: the caval-atrial junction, the sinoatrial node, the superior vena cava, the internal jugular vein, and the subclavian vein.

The method of positioning an endovascular device in the vasculature of a body may be further modified to include using the endovascular device to determine a location to secure a device within the vasculature of a body and then securing the endovascular device along with the device to the body to maintain the device in the location determined by the endovascular device. The method of positioning an endovascular device in the vasculature of a body may also include the steps of calculating a current position of the device and then comparing the calculated current position of the device to a location indicated by the processing step.

The steps of the method may be performed in any order or repeated in whole or in part to achieve the desired positioning or placement of the guided endovascular device. For example, the method of positioning an endovascular device in the vasculature of a body may include performing the processing step and the positioning step until the endovascular device is positioned within the right atrium relative to the coronary sinus. Alternatively, the method of positioning an endovascular device in the vasculature of a body may include performing the processing step and the positioning step until the endovascular device is positioned within the left atrium relative to a pulmonary vein. Alternatively, the method of positioning an endovascular device in the vasculature of a body may also include performing the processing step and the positioning step until the endovascular device is positioned within the aorta.

This aspect may be modified to include, for example, an additional step of displaying a result of the processing step. The processing step may also include information related to venous blood flow direction. The venous flow direction may also include a flow directed towards the sensor and a flow directed away from the sensor. Additionally or alternatively, the result of the processing step may also include one or more of information related to venous blood flow velocity, information related to venous blood flow signature pattern, information related to a pressure signature pattern, information related to ultrasound A-mode information; information related to a preferential non-random direction of flow within a reflected ultrasound signal, information related to electrical activity of the brain, information related to electrical activity of a muscle, information related to electrical activity of the heart, information related to the electrical activity of the sinoatrial node; and information about the electrical activity of the heart from an ECG.

In another aspect, the displaying step may also be modified to include a visual indication of the position of the device. The displaying step may also be modified to include a visual or color based indication of the position of the device alone or in combination with a sound based indication of the position of the device.

The method of positioning an endovascular device in the vasculature of a body may also be modified to include the step of collecting the reflected ultrasound signal in synchrony with an endovascular electrogram signal received by the sensor. Additional alternatives are possible such as where the endovascular electrogram comprises electrical activity from the heart, from the brain or from a muscle. The collection step may be timed to correspond to physiological actions or timings. For example, the collecting step is performed in synchrony during the PR interval or in synchrony with a portion of the P-wave.

Other portions of an EEG, ECG or EMG electrogram may also be used for timing of collecting, processing and/or storing information from device based or patient based sensors. In one aspect of the method of positioning an endovascular device in the vasculature of a body, the transmitting step, the



receiving step and the processing step are performed only when a selected endovascular electrogram signal is detected. In one version of the method, the selected endovascular electrogram signal is a portion of an ECG wave. In another version of the method, the selected endovascular electrogram signal is a portion of an EEG wave. In still another version of the method, the selected endovascular electrogram signal is a portion of an EMG wave.

The method of positioning an endovascular device in the vasculature of a body may also include identifying a structure in the vasculature using non-imaging ultrasound information in the reflected ultrasound signal. In one aspect, the non-imaging ultrasound information comprises using A-mode ultrasound to identify the structure in the vasculature. In another aspect, the non-imaging ultrasound information includes using Doppler ultrasound information to identify a flow pattern in proximity to the structure.

An another aspect of the method of positioning an endovascular device in the vasculature of a body the processing step is performed only on a portion of the reflected ultrasound signals that correspond to a selected electrogram trigger signal. This method may be employed, for example, when the selected electrogram trigger signal is a portion of an ECG wave, a portion of an EEG wave or a portion of an EMG wave.

In still other methods of positioning an endovascular device in the vasculature of a body, the processing step may be modified to include processing the reflected ultrasound signal by comparing the flow energy directed away from the endovascular device to the flow energy directed towards the endovascular device. In one aspect, there is a step of selecting for comparison the flow energy related to blood flow within the range of 2 cm/sec to 25 cm/sec.

In still other alternatives, the method of positioning an endovascular device in the vasculature of a body includes a processing step that has a step of processing the reflected ultrasound signal to detect an indicia of pulsatile flow in the flow pattern. The indicia of pulsatile flow may be any of a number of different parameters. The indicia of pulsatile flow may be: a venous flow pattern; an arterial flow pattern or an atrial function of the heart.

The method of positioning an endovascular device in the vasculature of a body may also include modification to the processing step to include the step of processing the endovascular electrogram signal to compare the relative amplitude of a P-wave to the relative amplitude of another portion of an electrocardiogram. In one aspect, the another portion of an electrocardiogram includes a QRS complex. The processing step may also be modified to include processing the reflective ultrasound signal to determine a blood flow velocity profile and processing the detected endovascular electrogram signal to determine a shape of the intravascular electrocardiogram. The processing step may be further modified to include the step of correlating the blood flow velocity profile and the shape of the intravascular electrocardiogram to determine the location of the endovascular device within the vasculature. Pulmonary Artery Peripherally Inserted Central Catheter (PA-PICC) and Pulmonary Artery Catheter (PAC)

A Pulmonary Artery Peripherally Inserted Central Catheter (PA-PICC) and a Pulmonary Artery Catheter (PAC) are typically used in procedures used to diagnose heart conditions, and measure parameters used to determine the cardiac function of a patient. These devices typically provide information regarding the central venous, right heart, and pulmonary arterial blood pressures, thermodilution measurements that are useful for calculating cardiac output and related physiological parameters, access for drug delivery, and blood sampling at various intervals along the length of the catheter. In some

embodiments, the PA-PICC or PAC balloon catheter systems of the invention may also provide ECG information along the pathway of the catheter from the central veins to the pulmonary artery.

In some embodiments, as shown in FIGS. 22A and 22B, the PA-PICC and/or the PAC systems comprise a balloon catheter 220 having a balloon 222 coupled to the catheter toward a distal end of the catheter. In some embodiments, the balloon catheter comprises elements of a conventional Swan-Ganz catheter, including a catheter measuring at least 55 to 75 cm in length, or any other suitable length, incremental markings to gauge insertion length (1-cm or 5-cm intervals, or any other suitable intervals), multiple lumens with an end-port at a tip of the catheter, and spaced side-ports which may be used for drug delivery, blood draws, mixed venous blood sampling, thermodilution measurement, pressure measurements at multiple locations simultaneously (may include pulmonary artery, pulmonary capillary wedge pressure, right ventricular, and central venous/right atrial pressure).

In some embodiments, as shown in FIGS. 22A and 22B, the PA-PICC and/or the PAC systems may also include a Doppler sensor (ultrasound transducer) 224 that is exposed at the distal tip of the catheter. In some embodiments, the ultrasound transducer may be coupled to a removal stylet. In some embodiments, one or more ECG (electrocardiogram) sensors 226 and/or ECG leads that may exist as part of the removable stylet or as a fixed member or members that may be integrated with the catheter tip or shaft. Leads may be spaced along the shaft of the catheter at various intervals to allow for optimal ECG signal detection and discrimination to guide catheter placement and to monitor cardiac electrical activity on a continuous basis. Subtle changes in electrical activity may correlate with normal and disease state physiology and changes in cardiac functional status as reflected in cardiac output and blood pressure fluctuations.

In some embodiments, the PA-PICC and/or the PAC systems may be placed through the same access as a standard Swan-Ganz catheter. The balloon catheter may be inserted in the same manner as a typical PICC using the upper arm basilic vein as the access vein of choice. In some embodiments, the balloon catheter may be inserted with ultrasound guidance. After inserting the PICC 25 to 30 cm, the balloon near the distal tip may be inflated with air and the catheter may slowly advanced as would be the case for a Swan-Ganz catheter inserted through a sheath into the internal jugular, subclavian, or femoral vein. In some embodiments, the Doppler sensor may activate during the placement process to identify the right atrium, right ventricle, pulmonary artery, and wedge position. Changes in the Doppler signature may indicate the relative position of the Doppler sensor during tip advancement and ultimate placement at the target. The ECG lead(s) may also indicate tip position as the catheter is placed.

In some embodiments, once the wedge position is reached and during times when the balloon is inflated for pressure measurements, cessation of blood flow as determined by loss of Doppler signal indicates that the wedge effect has been achieved. In the standard Swan-Ganz system, changes in the blood pressure measurements are used as an indication that flow within the pulmonary artery branch has ceased. Sometimes this inference is not entirely clear and the balloon may be inflated beyond the occlusion diameter and in the process of over-inflation, the pulmonary artery branch may be damaged or even rupture in rare instances with severe untoward consequences to the patient. Sudden hemorrhage and death have occurred from Swan-Ganz balloon-related trauma to the pulmonary arterial vasculature (Bossert T, Gummert J F, Bittner H B, Barten M, Walther T, Falk V, Mohr F W. Swan-Ganz



catheter-induced severe complications in cardiac surgery: right ventricular perforation, knotting, and rupture of a pulmonary artery. *J Card Surg.* 2006 May-June; 21(3):292-5.)

A PAC is generally used for diagnosis of heart conditions by measuring various parameters used to determine a patient's cardiac function. The PAC may be inserted percutaneously into a major vein such as the jugular, subclavian, or femoral vein. The PAC is inserted and advanced through the vasculature. In some embodiments, once the PAC is inserted a distance into the vasculature, for example inserted as far as the 30 cm mark on the catheter, if the femoral vein is the access location, the balloon is inflated with air. As the balloon is inflated, in some embodiments, changes in the measured cardiac waveform can be monitored. The PAC may provide circulatory pressure measurements including pulmonary artery pressure, left ventricle, left atrium, right atrium, and pulmonary artery occlusion pressure (also known as pulmonary artery wedge pressure). A PAC catheter may also measure cardiac output parameters, mixed venous oxygen saturation (SaO<sub>2</sub>), and/or oxygen saturations in the right heart chambers to assess for the presence of an intracardiac shunt for example. Using these measurements, other variables can be derived, including pulmonary or systemic vascular resistance and the difference between arterial and venous oxygen content. In some embodiments, pulmonary artery occlusion pressure (wedge pressure) may be measured when the PAC tip is positioned in a pulmonary artery wedge position (typically in a branch of the pulmonary artery) and the balloon is inflated. When the balloon is inflated and blocking flow, the pulmonary artery pressure tracing may disappear, and the resulting non-pulsatile pressure tracing is called the pulmonary capillary wedge pressure (PCWP), or pulmonary artery occlusion pressure. The PCWP is the back pressure that is exerted from the left heart "filling pressure".

#### Balloon Catheter System

As shown in FIGS. 22A and 22B, in some embodiments, the balloon catheter system includes a catheter 220 adapted and configured to be inserted into a patient's vasculature, an expandable balloon 222 coupled to the catheter towards the distal end of the catheter, and an ultrasound sensor 224 coupled to the catheter distal to the balloon. The balloon catheter system may be designed to detect parameters of a patient's cardiac function and, more specifically, to detect parameters of a patient's cardiac function while enabling the prevention of the balloon from over expanding and distending a vessel of a patient. The balloon catheter system may be alternatively used in any suitable environment and for any suitable reason.

In some embodiments, the balloon catheter is a Swan-Ganz catheter. The catheter in this embodiment may be at least 55 to 75 cm in length, or any other suitable length, having incremental markings to gauge insertion length (1-cm or 5-cm intervals, or any other suitable intervals). The catheter may include multiple lumens with an end-port at a tip of the catheter, and spaced side-ports which may be used for drug delivery, blood draws, mixed venous blood sampling, thermomodulation measurement, pressure measurements at multiple locations simultaneously (may include pulmonary artery, pulmonary capillary wedge pressure, right ventricular, and central venous/right atrial pressure).

As shown in FIGS. 22A and 22B, in some embodiments, the balloon 222 is expandable. As shown in FIG. 22A, the balloon has a first configuration. The first configuration may be a fully stowed configuration, or may alternatively be a partially inflated position as shown in FIG. 22A. By partially inflating the balloon, the blood flow within the vasculature of the patient may carry the balloon catheter once inserted by

pushing the partially inflated balloon along with the blood flow. As shown in FIG. 22B, the balloon is expandable such that it contacts the vessel wall, thereby substantially stopping the blood flow through the vessel.

As shown in FIGS. 22A and 22B, in some embodiments, the balloon catheter system may further include an ECG sensor 226 coupled to the catheter distal to the balloon. In some embodiments, the balloon catheter may include more than one ECG sensor. The ECG sensors and/or leads may be spaced along the shaft of the catheter at various intervals to allow for optimal ECG signal detection and discrimination to guide catheter placement and to monitor cardiac electrical activity on a continuous basis.

#### Methods for Evaluating Flow Characteristics

In some embodiments, as shown in FIG. 23, a method for evaluating flow characteristics in a vessel of a patient includes the steps of positioning a catheter having a balloon at a measuring location within the vessel, step 230; transmitting an ultrasound signal into the vessel while the balloon catheter is within the measuring location, step 232; evaluating a reflection of the ultrasound signal to determine a flow parameter within the vessel while the catheter is in the measuring position, step 234; expanding the balloon within the vessel at the measuring location, step 236; and stopping the expanding step when the result of the evaluating step is that the flow through the vessel is substantially stopped, step 238. The method may be designed for evaluating flow characteristics in a vessel of a patient and, more specifically, for evaluating flow characteristics in a vessel of a patient while enabling the prevention of a balloon from over-expanding and over-distending a vessel of a patient. The method may be alternatively used in any suitable environment and for any suitable reason.

Step 230, which recites positioning a catheter having a balloon at a measuring location within the vessel, may function to advance the balloon catheter through the vasculature of a patient to the measuring location. In some embodiments, the measuring location may be within a pulmonary artery. In some embodiments, the measuring location may be within a branch of the pulmonary artery, while in some embodiments, the measuring location may be in a pulmonary artery wedge position. The wedge position is a location at which the balloon when expanded will obstruct the lumen of the blood vessel and thereby halt blood flow through the vessel. In some embodiments, the balloon may also be expanded in the superior vena cava (SVC) and may act as a "sail" as the blood flow drags the catheter through the right side of the heart until the balloon lodges in a pulmonary artery branch. The site where the balloon lodges may be the wedge position, and in some embodiments, may be the position where the catheter tip may reside once the catheter is secured at the skin insertion site, which in some embodiments, is located in the neck.

In some embodiments, step 230, the positioning step, may further include the steps of advancing the balloon catheter into the vessel, transmitting an ultrasound signal into the vessel using an ultrasound transducer on the balloon catheter, receiving a reflected ultrasound signal with the ultrasound transducer, and positioning the endovascular device based on the ultrasound signal. In some embodiments, the ultrasound signal is reflected within the vessel. This reflected signal may be received by an ultrasound sensor on the balloon catheter. In some embodiments, the receiving ultrasound transducer is the same transducer as the transmitting transducer. The reflected ultrasound signal may be used to determine any number of characteristics or parameters that may be useful in the guidance of the catheter during the positioning step. These flow parameters may include, but are not limited to, blood flow velocity, blood flow intensity, blood flow direction

(blood flow towards the transducer and/or blood flow away from the transducer), blood flow signature pattern, pressure signature pattern, spectrum characteristics, amplitude characteristics, ultrasound A-mode information, or any other suitable parameters and/or information. Ultrasound guidance of a catheter through the vasculature of a patient is described in detail above.

Step 232, which recites transmitting an ultrasound signal into the vessel while the balloon catheter is within the measuring location, may function to send an ultrasound signal into a vessel in order to detect characteristics about the vessel, and or the blood flow through the vessel in and around the measuring location. The ultrasound signal may be transmitted from an ultrasound transducer coupled to the balloon catheter. In some embodiments, the ultrasound sensor is coupled to the balloon catheter distal to the balloon. The ultrasound signal transmitted into the vessel may include a non-imaging ultrasound signal, an A-mode ultrasound signal, and/or a Doppler ultrasound signal. In some embodiments, the transmitting step is preformed throughout the expanding step, or may alternatively be performed repeatedly after multiple expanding steps, wherein the balloon may be expanded an amount each time the expansion step is performed.

Step 234, which recites evaluating a reflection of the ultrasound signal to determine a flow parameter within the vessel while the catheter is in the measuring position, may function to determine detect characteristics about the vessel, and or the blood flow through the vessel from the ultrasound signal. In some embodiments, the evaluating step includes receiving a reflected ultrasound signal with an ultrasound transducer on the balloon catheter. In some embodiments, the ultrasound transducer that transmits the signal is the same transducer that receives the signal. In some embodiments, the flow parameter determined is the blood flow velocity and/or blood flow intensity within the vessel. In some embodiments, the flow parameter determined is the blood flow signature pattern within the vessel, while in some embodiments, the flow parameter determined is a pressure signature pattern within the vessel. The flow parameter determined may alternatively be any other suitable parameter, and/or any suitable combination of parameters.

Step 236, which recites expanding the balloon within the vessel at the measuring location, may function to initiate and/or complete the occlusion of the vessel with the balloon, in order to block the flow through the vessel. Step 238, which recites stopping the expanding step when the result of the evaluating step is that the flow through the vessel is substantially stopped, may function to stop the expansion of the balloon such that the balloon has expanded to the point where it has just contacted the wall of the vessel and/or substantially stopped the flow through the vessel but has not yet over-expanded into the vessel wall. In some embodiments, the balloon is preferably expanded to the point of contacting the vessel wall and stopping the flow of blood through the vessel, while the balloon is preferably not expanded to the point where the balloon over-extends the vessel wall. In some embodiments, the stopping step further comprises stopping the expansion of the balloon when the ultrasound transducer receives a reflected ultrasound signal that indicates that the flow through the vessel has substantially stopped.

In some embodiments, the evaluating step determines the blood flow velocity within the vessel and the stopping step further comprises stopping the expanding step when the determined blood flow velocity and/or blood flow intensity indicates that the flow through the vessel has substantially stopped. In some embodiments, the blood flow velocity and/or blood flow intensity will indicate that the flow through the

vessel has substantially stopped when the velocity changes from a velocity in substantially a single direction to a velocity in multiple directions. The velocity may initially increase, and in some embodiments, may eventually drop to zero.

In some embodiments, the evaluating step determines the blood flow signature pattern within the vessel and the stopping step further comprises stopping the expanding step when the determined blood flow signature pattern indicates that the flow through the vessel has substantially stopped.

In some embodiments, the evaluating step determines the pressure signature pattern within the vessel and the stopping step further comprises stopping the expanding step when the determined pressure signature pattern indicates that the flow through the vessel has substantially stopped. In some embodiments, the pressure signature pattern indicated that the flow through the vessel has substantially stopped by the pressure level dropping. In some embodiments, the stopping step further comprises stopping the expanding step when the result of the evaluating step is that the pressure at the measuring location within the vessel has dropped below the mean pulmonary arterial pressure. In some embodiments, the stopping step further comprises stopping the expanding step when the result of the evaluating step is that the pressure signature pattern at the measuring location within the vessel is consistent with a pulmonary capillary wedge pressure signature pattern. In some embodiments, the pressure signature pattern indicates a pressure lower than a pulmonary artery pressure and a pressure more static than a pulmonary artery pressure. In some embodiments, the stopping further comprises stopping the expanding step when the balloon expanding pressure is at least equal to a systolic pulmonary arterial pressure.

In some embodiments, as shown in FIG. 24 the method may further comprise step 240, which recites deflating the balloon. The balloon may be deflated to a stowed configuration, or may alternatively be deflated to a partially inflated configuration. By deflating the balloon, the blood flow past the balloon and through the vessel may begin to return (i.e. increase from substantially zero). In some embodiments, the balloon is preferably in the stowed configuration while it is removed from the vasculature. It may be easier to move the balloon through the vasculature while the balloon is in a deflated configuration.

In some embodiments, the evaluating step may further comprise step 242, which recites evaluating a reflection of the ultrasound signal to determine a flow parameter within the vessel after the balloon is deflated. In some embodiments, the flow parameter determined may be the blood flow signature pattern within the vessel, or any other suitable flow parameter or information. In some embodiments, as the balloon deflates and decouples from the vessel wall, the blood flow signature pattern may indicate the resulting turbulent blood flow, and/or the general return of the blood flow past the balloon. In some embodiments, the method may further include step 244, which recites verifying that flow parameter within the vessel determined after the balloon is deflated is substantially similar to the flow parameter within the vessel determined before the balloon is inflated. This step may function to verify that blood flow has returned to normal flow (i.e. baseline flow, in some embodiments measured before the expansion of the balloon). This step may function as a safety feature of the balloon catheter.

In some embodiments, as shown in FIG. 25 the method may further comprise step 250, which recites detecting an endovascular electrogram signal with a sensor on the endovascular device. In some embodiments, the endovascular electrogram comprises electrical activity from the heart, and in some embodiments, the electrical activity of the heart is

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related to the sino-atrial node of the heart. In some embodiments, ECG sensors may be spaced along the catheter at various intervals to allow for optimal ECG signal detection and discrimination to guide catheter placement and/or to monitor cardiac electrical activity on a continuous basis. Subtle changes in electrical activity may correlate with normal and disease state physiology and changes in cardiac functional status as reflected in cardiac output and blood pressure fluctuations. In some embodiments, the timing of the expanding step may be based on the electrogram signal. In some embodiments, the result of the evaluating step is a combined evaluation of the ultrasound signal and the electrogram signal.

In some embodiments, as shown in FIG. 25 the method may further comprise step 252, which recites measuring a parameter used to determine cardiac function. In some embodiments, the parameter may be pulmonary artery occlusion pressure or any other suitable parameter such as cardiac output. In some embodiments, the timing of the measuring step is based on the detected electrogram signal.

In some embodiments, as shown in FIG. 26, a method for evaluating flow characteristics in a vessel of a patient includes the steps of positioning a catheter having a balloon at a measuring location within the vessel, step 260; transmitting a first ultrasound signal into the vessel while the balloon catheter is within the measuring location, step 261; evaluating a reflection of the first ultrasound signal to determine a first flow parameter of the vessel while the balloon is in a first configuration, step 262; expanding the balloon within the vessel at the measuring location, step 263; transmitting a second ultrasound signal into the vessel during the expanding step, step 264; evaluating a reflection of the second ultrasound signal to determine when the blood flow through the vessel is substantially stopped, step 265; returning the balloon to the first configuration, step 266; transmitting a third ultrasound signal into the vessel after the returning step, step 267; and evaluating a reflection of the third ultrasound signal to determine a third blood flow parameter of the vessel, step 268. The method may be designed for evaluating flow characteristics in a vessel of a patient and, more specifically, for evaluating flow characteristics in a vessel of a patient while enabling the prevention of a balloon from over-expanding and over-distending a vessel of a patient. The method may be alternatively used in any suitable environment and for any suitable reason.

Step 266, which recites returning the balloon to the first configuration, may function to deflate the balloon such that it returns to the first configuration. As described, the first configuration may be a stowed configuration, or may alternatively be a partially inflated configuration. By returning the balloon to the first configuration, the blood flow past the balloon and through the vessel may begin to return, and it may be easier to move the balloon through the vasculature while the balloon is in the first configuration. In some embodiments, the balloon is preferably in the stowed configuration while it is removed from the vasculature.

Step 267, which recites transmitting a third ultrasound signal into the vessel after the returning step, may function to send an ultrasound signal into the vasculature as the blood flow past the balloon and through the vessel may begin to return. Step 268, which recites evaluating a reflection of the third ultrasound signal to determine a third blood flow parameter of the vessel, may function to detect a flow parameter of the blood flow through the vessel and/or past the deflating/deflated balloon. In some embodiments, the third flow parameter determined may be the blood flow signature pattern within the vessel, or any other suitable flow parameter or information. In some embodiments, as the balloon deflates

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and decouples from the vessel wall, the blood flow signature pattern may indicate the resulting turbulent blood flow, and/or the general return of the blood flow past the balloon. In some embodiments, the method may further include the step of verifying that third flow parameter within the vessel determined after the balloon is deflated is substantially similar to the first flow parameter within the vessel determined before the balloon is inflated. This step may function to verify that blood flow has returned to normal flow (i.e. baseline flow, in some embodiments measured before the expansion of the balloon). This step may function as a safety feature of the balloon catheter.

In some embodiments, as shown in FIG. 27, a method for evaluating flow characteristics in a vessel of a patient includes the steps of positioning a catheter having a balloon at a measuring location within the vessel, step 270; transmitting an ultrasound signal into the vessel while the balloon catheter is within the measuring location, step 271; detecting an electrogram signal while the balloon catheter is within the measuring location, step 272; evaluating a reflection of the ultrasound signal and the electrogram signal while the catheter is in the measuring position, step 273; expanding the balloon within the vessel at the measuring location, step 274; stopping the expanding step when the result of the evaluating step is that the flow through the vessel is substantially stopped, step 275; and measuring a parameter used to determine cardiac function, wherein the timing of the measuring step is based on the result of the evaluation step, step 276. In some embodiments, the result of the evaluating step is a combined evaluation of the ultrasound signal and the electrogram signal. The method may be designed for evaluating flow characteristics in a vessel of a patient and, more specifically, for evaluating flow characteristics in a vessel of a patient while enabling the prevention of a balloon from over-expanding and over-distending a vessel of a patient. The method may be alternatively used in any suitable environment and for any suitable reason.

While preferred embodiments of the present invention have been shown and described herein, it will be obvious to those skilled in the art that such embodiments are provided by way of example only. Numerous variations, changes, and substitutions are incorporated herein by reference in their entirety. It is intended that the following claims define the scope of the invention and that methods and structures within the scope of these claims and their equivalents be covered thereby.

What is claimed is:

1. A method of evaluating flow characteristics in a vessel of a patient, the method comprising:
  - inserting a catheter comprising a balloon, an ultrasound transducer and an endovascular electrogram sensor into the vessel of the patient, wherein the ultrasound transducer is distal of the balloon and the endovascular electrogram sensor when the balloon is expanded;
  - transmitting, from the ultrasound transducer of the catheter, a first non-imaging ultrasound signal into the vessel when the balloon is not expanded;
  - receiving a first reflected non-imaging ultrasound signal;
  - detecting an endovascular electrogram signal using the endovascular electrogram sensor;
  - determining, using a processor, a first blood flow signature pattern within the vessel based on the first reflected non-imaging ultrasound signal, the first blood flow signature pattern being different from the first reflected non-imaging ultrasound signal;

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determining, using the processor, the location of the catheter within the vessel based on the first blood flow signature pattern and the detected endovascular electrogram signal;

initiating expansion of the balloon within the vessel at a measuring location within the vessel, the measuring location within the vessel being different from the determined location within the vessel;

transmitting, from the ultrasound transducer of the catheter, a second non-imaging ultrasound signal into the vessel while the balloon is being expanded;

receiving a second reflected non-imaging ultrasound signal;

determining, using the processor, a second blood flow signature pattern within the vessel based on the second reflected non-imaging ultrasound signal, the second blood flow signature pattern being different from the first blood flow signature pattern and from the second reflected non-imaging ultrasound signal;

determining that the second blood flow signature pattern indicates that flow through the vessel has stopped; and

stopping the expansion of the balloon while maintaining the stoppage of flow through the vessel in response to the determination that the second blood flow signature pattern indicates that flow through the vessel has stopped.

2. The method of claim 1, wherein the measuring location is within a pulmonary artery.

3. The method of claim 2, wherein the measuring location is within a branch of the pulmonary artery.

4. The method of claim 2, wherein the measuring location is a pulmonary artery wedge position.

5. The method of claim 1, wherein the ultrasound signals are A-mode ultrasound signals.

6. The method of claim 1, wherein the ultrasound signals are Doppler ultrasound signals.

7. The method of claim 1, wherein the blood flow signature patterns are blood flow velocities.

8. The method of claim 1, wherein the blood flow signature patterns are pressure signature patterns.

9. The method of claim 1, further comprising:

determining a pressure at the measuring location;

determining that the pressure at the measuring location is below a mean pulmonary arterial pressure; and

stopping the expansion of the balloon while maintaining the stoppage of flow through the vessel comprises stopping the expansion of the balloon while maintaining the stoppage of flow through the vessel in response to the determination that the pressure at the measuring location is below the mean pulmonary arterial pressure.

10. The method of claim 8, wherein stopping the expansion of the balloon while maintaining the stoppage of flow through the vessel comprises stopping the expansion of the balloon while maintaining the stoppage of flow through the vessel in response to a determination that a pressure signature pattern at the measuring location is consistent with a pulmonary capillary pressure signature pattern.

11. The method of claim 10, wherein the pressure signature pattern indicates a pressure lower than a pulmonary artery pressure and more static than a pulmonary artery pressure.

12. The method of claim 1, further comprising deflating the balloon at the measuring location after stopping the expansion of the balloon.

13. The method of claim 12, further comprising:

transmitting, from the ultrasound transducer of the catheter, a third non-imaging ultrasound signal into the vessel after the balloon is deflated;

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receiving a third reflected non-imaging ultrasound signals; and

determining, using the processor, a third blood flow signature pattern within the vessel based on the third reflected non-imaging ultrasound signal, the third blood flow signature pattern being different from the third reflected non-imaging ultrasound signal.

14. The method of claim 13, wherein the third blood flow signature pattern indicates turbulent blood flow after the balloon deflates and decouples from the vessel wall.

15. The method of claim 1, wherein the endovascular electrogram signal comprises electrical activity of the heart.

16. The method of claim 15, wherein the electrical activity of the heart is related to the sino-atrial node of the heart.

17. The method of claim 1, wherein initiating expansion of the balloon within the vessel at the measuring location comprises timing the initiation of the expansion of the balloon based on the endovascular electrogram signal.

18. The method of claim 1, further comprising measuring a parameter used to determine cardiac function.

19. The method of claim 18, wherein the parameter is pulmonary artery occlusion pressure.

20. The method of claim 18, wherein the parameter used to determine cardiac function is based on the endovascular electrogram signal.

21. The method of claim 20, wherein the parameter is arterial flow.

22. The method of claim 1, wherein the first blood flow signature pattern is a blood flow direction.

23. The method of claim 22, wherein the blood flow direction comprises a blood flow directed towards the ultrasound transducer or a blood flow directed away from the ultrasound transducer.

24. The method of claim 1, wherein the first blood flow signature pattern is a blood flow velocity.

25. A method of evaluating flow characteristics in a vessel of a patient, the method comprising:

inserting a catheter comprising a balloon, an ultrasound transducer and an endovascular electrogram sensor into the vessel of the patient;

transmitting, from the ultrasound transducer of the catheter, a first non-imaging ultrasound signal into the vessel;

receiving a first reflected non-imaging ultrasound signal;

detecting an endovascular electrogram signal using the endovascular electrogram sensor;

determining, using a processor, a first flow parameter within the vessel based on the first reflected non-imaging ultrasound signal, the first flow parameter being different from the first reflected non-imaging ultrasound signal;

determining, using the processor, the location of the catheter within the vessel based on the first flow parameter and the detected endovascular electrogram signal;

transmitting, from the ultrasound transducer of the catheter, a second non-imaging ultrasound signal into the vessel while the catheter is at a measuring location within the vessel, the measuring location within the vessel being different from the determined location within the vessel;

receiving a second reflected non-imaging ultrasound signal;

determining, using the processor, a second flow parameter of the vessel based on the second reflected non-imaging ultrasound signal while the balloon is in a first configuration, the second flow parameter being different from

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the first flow parameter and from the second reflected non-imaging ultrasound signal;  
 initiating expansion of the balloon within the vessel at the measuring location within the vessel;  
 transmitting, from the ultrasound transducer of the catheter, a third ultrasound signal into the vessel while the balloon is being expanded;  
 receiving a third reflected non-imaging ultrasound signal;  
 determining, using the processor, a third flow parameter of the vessel based on the third reflected non-imaging ultrasound signal, the third flow parameter being different from the first flow parameter, from the second flow parameter and from the third reflected non-imaging ultrasound signal;  
 determining that the third flow parameter indicates that the flow through the vessel has stopped;  
 returning the balloon to the first configuration after determining that the third flow parameter indicates that the flow through the vessel has stopped;  
 transmitting a fourth ultrasound signal into the vessel after the balloon is returned to the first configuration;  
 receiving a fourth reflected non-imaging ultrasound signal;  
 determining, using the processor, a fourth flow parameter of the vessel based on the fourth reflected non-imaging ultrasound signal, the fourth flow parameter being different from the first flow parameter, from the second flow parameter, from the third flow parameter and from the fourth reflected non-imaging ultrasound signal;  
 comparing the second flow parameter with the fourth flow parameter; and  
 determining, in response to the comparison of the second flow parameter to the fourth flow parameter, that the second flow parameter is equal to the fourth flow parameter to verify that the blood flow through the vessel has returned to the same state that existed before the balloon was expanded.

26. The method of claim 25, wherein the first configuration of the balloon is a stowed configuration.

27. The method of claim 25, wherein the first configuration of the balloon is a partially inflated configuration.

28. The method of claim 25, wherein the first flow parameter, the second flow parameter, the third flow parameter, and the fourth flow parameter are blood flow signature patterns.

29. A method of evaluating flow characteristics in a vessel of a patient, comprising:  
 inserting a catheter comprising a balloon, an ultrasound transducer and an endovascular electrogram sensor into the vessel of the patient, wherein the ultrasound transducer is distal of the balloon and the endovascular electrogram sensor when the balloon is expanded;  
 transmitting, from the ultrasound transducer of the catheter, a first non-imaging ultrasound signal into the vessel when the balloon is not expanded;  
 receiving a first reflected non-imaging ultrasound signal;  
 detecting a first endovascular electrogram signal using the endovascular electrogram sensor;  
 determining, using a processor, a first blood flow signature pattern within the vessel based on the first reflected non-imaging ultrasound signal, the first blood flow signature pattern being different from the first reflected non-imaging ultrasound signal;  
 determining, using the processor, the location of the catheter within the vessel based on the first blood flow signature pattern and the first endovascular electrogram signal;  
 initiating expansion of the balloon within the vessel at a measuring location within the vessel;

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transmitting, from the ultrasound transducer of the catheter, a second non-imaging ultrasound signal into the vessel while the balloon is being expanded;  
 receiving a second reflected non-imaging ultrasound signal;  
 determining, using the processor, a second blood flow signature pattern within the vessel based on the second reflected non-imaging ultrasound signal, the second blood flow signature pattern being different from the first blood flow signature pattern and from the second reflected non-imaging ultrasound signal;  
 stopping the expansion of the balloon while maintaining the stoppage of flow through the vessel in response to the determination that the second blood flow signature pattern indicates that the flow through the vessel is stopped;  
 detecting, from the endovascular electrogram sensor, a second endovascular electrogram signal; and  
 using the second endovascular electrogram signal to trigger the transmitting steps or determining steps.

30. The method of claim 29, wherein the second blood flow signature pattern is a pressure signature pattern.

31. The method of claim 1, further comprising determining a mean pulmonary arterial pressure.

32. The method of claim 24, wherein the blood flow velocity is a blood flow velocity towards the catheter or a blood flow velocity away from the catheter.

33. The method of claim 1, wherein the first blood flow signature pattern is a blood flow power spectrum towards the catheter or a blood flow power spectrum away from the catheter.

34. The method of claim 25, wherein the ultrasound transducer is distal of the balloon when the balloon is expanded.

35. The method of claim 1, wherein:  
 receiving the first reflected non-imaging ultrasound signal comprises receiving, using the ultrasound transducer of the catheter, the first reflected non-imaging ultrasound signal; and  
 receiving the second reflected non-imaging ultrasound signal comprises receiving, using the ultrasound transducer of the catheter, the second reflected non-imaging ultrasound signal.

36. The method of claim 25, wherein:  
 receiving the first reflected non-imaging ultrasound signal comprises receiving, using the ultrasound transducer of the catheter, the first reflected non-imaging ultrasound signal;  
 receiving the second reflected non-imaging ultrasound signal comprises receiving, using the ultrasound transducer of the catheter, the second reflected non-imaging ultrasound signal;  
 receiving the third reflected non-imaging ultrasound signal comprises receiving, using the ultrasound transducer of the catheter, the third reflected non-imaging ultrasound signal; and  
 receiving the fourth reflected non-imaging ultrasound signal comprises receiving, using the ultrasound transducer of the catheter, the fourth reflected non-imaging ultrasound signal.

37. The method of claim 29, wherein:  
 receiving the first reflected non-imaging ultrasound signal comprises receiving, using the ultrasound transducer of the catheter, the first reflected non-imaging ultrasound signal; and  
 receiving the second reflected non-imaging ultrasound signal comprises receiving, using the ultrasound transducer of the catheter, the second reflected non-imaging ultrasound signal.